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FLUIDIC RELIABILITY

By

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Darrell Bengston

June 1968

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-67-C-0003

HONEYWELL INC.

AEROSPACE DIVISION

MINNEAPOLIS, MINNESOTA

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FLUIDIC RELIABILITY

Final Report

Honeywell Document 20810-FR1

By

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Prepared by

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U. S. ARMY AVIATION MATERIEL LABORATORIES
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SUMMARY

The objective of this contract was to develop quantitative information concerning the reliability and maintainability of hydraulic fluidic components and systems. This was accomplished by testing a feasibility-model hydraulic single-axis stability augmentation system (SAS) under conditions simulating actual flights of a UH-1B helicopter and, along with 15 of each type of component making up the SAS, life testing under environmental conditions of 0.5-g and 2.0-g vibration, temperature from -30°F to +200°F, and cycling of the component input signals. Also tested were 15 bistable amplifiers. The components were divided into environmental and nonenvironmental groups, with the environmental group divided into groups subject to 50-micron oil and 10-micron oil. This made up the 15 components, five in each of the three groups.

The feasibility SAS and the components making up the SAS completed the testing with no failures. While the bistable amplifiers did not meet the failure limits, they still had enough gain to switch another like amplifier. The results of this program show that fluidic components and systems are very reliabe.

Since fluidic components appear to fail only in a wearout mode, more components should be tested for longer periods of time to determine their life and how they fail.

FOREWORD

This document concludes a reliability program authorized by the U. S. Army Aviation Materiel Laboratories under Contract DAAJ02-67-C-0003. The Technical Monitor for this program is Mr. G. W. Fosdick. The objective is to demonstrate the reliability of hydraulic fluidic components used in helicopter aircraft. The program is a part of the continuing effort by the U. S. Army to obtain stabilization systems for helicopters that are reliable, lightweight, inexpensive, easily maintained, and readily stored. The work presented in this report was initiated 21 December 1966 and completed 15 January 1968.

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LIST OF SYMBOLS

μ	-	micron
%	-	percent
λ	-	failure rate
N	-	number of components of a given type
deg	-	degree
ΔP	-	differential pressure
d-c	-	direct current
a-c	-	alternating current
in.	-	inches
deg/sec	-	degrees per second
psi	-	pounds per square inch
gpm	-	gallons per minute
CW	-	clockwise
CCW	-	counterclockwise
in^3/min	-	cubic inches per minute
v	-	volts
Ps	-	supply pressure
β	-	side slip angle caused by wind gusts
θ	-	pilot rudder command angle
% O.S.	-	percent overshoot
γ	-	damping ratio
V_M	-	vent return

LIST OF SYMBOLS (CONCLUDED)

Adj	-	adjust
+	-	symbol to show polarity
Gain set	-	resistor used to adjust system gain

SECTION I

INTRODUCTION

This final report describes the effort to demonstrate the reliability of hydraulic fluidic components that make up a single-axis stability augmentation system (SAS) plus hydraulic bistable amplifiers.

Fifteen sets of components were subjected to various environments and oil contaminations for approximate test times of 3000 hours per component and a total of 45,000 hours per component type. A SAS which was fabricated under Contract DA 44-177-AMC-294(T) was also subjected to a number of simulated helicopter flights and then subjected to the life test for the remaining time. From the data obtained, the reliability and maintainability of the components and systems were evaluated.

SECTION II
RESULTS

RELIABILITY RESULTS

The Fluidic Reliability Program was successful in generating data which provided further insight into the reliability and maintainability of fluidic components and systems. These data are summarized in Table I.

As a result of this program, it was concluded that the reliability of fluidic components (and therefore, systems) cannot be evaluated using conventional reliability techniques, since fluidic component degradation does not conform to the exponential distribution with its associated random failures but, rather, to the normal distribution characteristic of wearout failures. Therefore, no degradation failures are expected until the fluidic component life approaches the mean life of that type of component and the device physically begins to deteriorate. Thus, the component failure rate will essentially remain at zero until wearout occurs. This is not expected to occur until well beyond the normal operational or technological life of a typical system and/or aircraft. In addition, no catastrophic failure modes were identified for fluidic components. Fluidic components may experience parameter shifts which might degrade system performance, but they will not experience a catastrophic failure which would result in complete cessation of system performance. This is a distinct advantage over electronic systems.

To facilitate the estimation of fluidic system reliability and comparisons with equivalent electronic systems, a list of projected failure rates was derived and used to prepare a yaw damper system mean-time-between-failure (MTBF) estimate. This estimate was then used to compare the potential reliabilities of the fluidic and equivalent electromechanical yaw damper systems. These MTBF's are 83, 000 hours for the fluidic system and 9000 hours for the electromechanical system.

Not enough data was generated, due to the lack of failures, to determine repair time of fluidic components or systems. The repair time is estimated to be two to four hours. This is higher than the estimate for an equivalent electromechanical system, but, when combined with the high mean-time-between-repair of the fluidic system, the overall maintainability and resultant fluidic system availability will be superior to that of the electromechanical system.

TABLE I. RELIABILITY RESULTS

Device/Unit	Operating Hours	Failures	Failure Rate (Best Estimate)		MTBF (Best Estimate)	
			Achieved (%/1000 Hours)	Poisson (%/1000 Hours)	Achieved (Hours)	Poisson (Hours)
Feasibility System	1912	0	-	-	NA	2730
Synthesized Systems	24, 686	0	-	-	NA	35, 266
Rate Sensor	48, 466[1]	0	0	1. 44	-	-
Proportional Amplifier	55, 859[1]	0	0	1. 25	-	-
Bellows	49, 164[1]	0	0	1. 42	-	-
Trim Control	44, 890[1]	0	0	1. 56	-	-
Bistable Amplifier	46, 846	15[2]	(2)	(2)	-	-

[1] Includes system test hours

[2] Units were operational; failure limits are questionable.

TECHNICAL RESULTS

This section contains a discussion of the various components and of the feasibility system fabricated under Contract DA 44-177-AMC-294(T).

Vortex Rate Sensor

All 16 rate sensors had adjustable pickoffs, and, during the preliminary tests, all 16 were adjusted so that the differential output signal for zero input turning rate was zero. The null of the sensors varied appreciably during the life test. The technique used in designing the pickoffs was the same as that used in pneumatic units; however, because of the higher density fluid and, subsequently, the higher force on the pickoff blade, this technique should not be used in any future higher density fluid units. This was also substantiated by the sensor work done on the feasibility system where a fixed blade was installed; system null then remained constant. Even though null did not exceed the failure limit during this testing, the null stability could be greatly improved by installing a fixed pickoff blade. Noise from the rate sensors, measured when mounted in the life test manifold, was quite high in the ±10 deg/sec range. The noise measured during the preliminary checks when tested individually was approximately ±2 deg/sec. Again, using the information learned from testing the feasibility system and from the life test, manifolding played a large part in the noise measured at the sensor pickoff ports.

The initial performance tests were conducted holding the inlet pressure constant and monitoring the total flow to each group of sensors. After the first two weeks of running and after the performance tests were made, the flow to each package increased. Since the sensor is a flow device, the gain also increased. It was decided to change the input criteria and to run each group of sensors at a constant flow, even though the flow distribution to the five sensors would not be known. Testing of the hydraulic oil showed that the viscosity decreased during the first few hundred hours of the life test, which caused the increase in flow for a constant pressure.

After completion of the life test, the units were disassembled and examined. The units running on 50-micron oil were quite dirty at the outer diameter of the coupling element. (Only the 50-micron sensors were like this.) Examination of the contamination showed that it was Styrofoam, the insulation used on the reservoirs and heat exchangers. The pumping systems initially were run with no components installed. The oil was then drained, the filters were replaced, and new oil was added, which should have cleaned the pumping systems. At the beginning of the life test, the filters did bypass; however, this occurred in both systems

and was not unique to the 50-micron system. Possibly, even with the precaution of cleaning the pumping system, some contamination initially lodged itself outside the main stream and, over a period of time, due to the temperature cycling and vibration, dislodged the contaminant and it got into the sensors. Most of the contamination would go into the sensors, since they draw much more flow than the other components.

The vortex rate sensors performed very well, regardless of the contamination or environment. None of the units failed the life test, either by a catastrophic failure or a performance failure. However, the units could be improved by redesigning the pickoff to incorporate a fixed blade, since it has been shown in the flight simulation tests that the adjustable blade is not needed and does degrade the sensor performance. An additional benefit of the flight simulation test is that manifolding plays a major roll in the amount of noise the sensor produces.

Proportional Amplifier

The nulls of the proportional amplifier varied a great deal. The amplifiers were made approximately four inches square to facilitate manifolding and testing. During the initial running of the amplifiers in the manifolds, amplifier weeping occurred (oil slowly oozed from between the amplifier plate and the top plate). The amplifiers were removed, the plates were lapped again, and a thin film of vacuum grease was applied to the top plate. (Gaskets cannot be used because they extrude into the amplifier channels and affect the unit's performance.) The units still weeped, but at a lower rate. (The large surface area of the amplifiers make it relatively impossible to seal the units.) The leakage probably varied over the period of the life test, causing the variations in null that were experienced. Much improvement could be realized by reducing the contact area or by electroforming the amplifiers onto a mounting plate which eliminates all leakage, internal or external (this method was successfully used for the flight test model fabrication on Contract DAAJ02-67-C-0056.)

As with the rate sensors, it was necessary to test the amplifiers at constant flow instead of constant pressure. However, with the amplifiers, it was possible, with the original manifolding, to test the units individually. This allowed the input parameters, flow and pressure, to be monitored for each individual unit.

No proportional amplifiers failed any of the limits prescribed at the beginning of the life test. Actual tactical units would perform even better than the units tested under this contract, since it would not be necessary to have any manifolding in the units. This would allow the units to be made smaller with subsequent higher clamping pressures. In fact, both this type and an electroformed amplifier were subjected to pressures greater than 700 psig with no leakage.

Bellows

The bellows performed perfectly throughout the life test. The 50-micron units were accidentally overpressured early in the test and were replaced. This overpressure could never occur in a system, because the supply pressure in a system is only about 20 psig and tests have shown that it takes 55 psig to damage the bellows. In the life test, the 90-psig supply was throttled to approximately 2 psig. There was also a valve on the return line to facilitate performance testing. If the return line valve plugged momentarily, the bellows would be subjected to 90 psig, more than enough to damage the bellows.

Trim Control Valves

The trim control valves on the 50-micron oil system ceased operating immediately after they were energized with oil, since they had only 10-micron internal filters. The filters were replaced with 50-micron filters, and the valves functioned properly for the remainder of the test.

The trim control valves were purchased items and performed within the failure limits throughout the life test.

Bistable Amplifiers

The program goal was to obtain bistable amplifiers compatible with the other system components in terms of power consumption and other operating parameters. It was not practical to design a hydraulic bistable amplifier using the wall attachment effect, since it is necessary to have high Reynolds number flow through the power nozzle. In this case it would have meant a very large amplifier using a large amount of flow or, on the size finally selected, using a very high pressure. It was possible, using the proper loads and adding a cusp to the splitter of the amplifier, to obtain bistability. The cusp provided internal positive feedback, causing the amplifier to switch hardover after a certain input signal level was reached. This allowed the unit to be no larger than a conventional hydraulic proportional amplifier and to use no more power.

The null and gain of the bistable amplifier varied widely during the testing. A number of techniques were used to correct the problem, but nothing changed the performance. An accumulator was added to reduce noise; the units were tested under constant flow, under constant pressure, in groups manifolded together, and individually. Part of the problem was the same as for the proportional amplifiers: leakage. Null and gain are interrelated for bistable amplifiers; if the switch point changes, going from the right leg to the left, but

does not change when switching back, the null which is the midpoint between the two switch points will change. The gain, which is the output divided by the difference between the switch points, will also change.

It is believed that the gain variation, etc., was caused by changes in the feedback from the cusp, by noise, or by other external flow and pressure changes. It should also be noted that the gain never reduced below the level necessary to switch another like amplifier.

Hydraulic Damper System

The hydraulic damper system, which was designed, fabricated, and tested under Contract DA 44-177-AMC-294(T), was a feasibility model to demonstrate that fluidic components could provide the proper damping in the UH-1B helicopter. The system was reworked prior to testing under this contract. During the initial checkout prior to the flight profile simulation tests, the system exhibited a gain change of approximately two when the rate sensor orientation was changed. This particular sensor had never been tested in any other orientation and was the first sensor to exhibit this phenomenon. After limited investigation and to expedite the program, the sensor was replaced with one of the life test units. To do this, it was necessary to change the system manifolding; in the process, the system noise level became very high. By reworking the manifolding and installing a fixed blade in the sensor, the noise was reduced to a level below the specified limit. The system was then subjected to thirty 2-hour cycles simulating the flight environment of an actual helicopter. The cycle began with the oil and ambient temperature at -25°F and concluded with the ambient temperature at +100°F and the oil temperature at +200°F. After the fifth cycle, the mechanical trim valve moved, and it was necessary to renull the system. During the performance test, after cycles 15 and 25, it was necessary to clean the system because of contamination. The filter was bypassing during the first part of the test and allowed contamination to enter the system. Following the flight profile tests, the system was mounted on the life test fixture along with the components. Another 1912 hours of time was accumulated on the system, at which time the life test components reached the required 3000 hours and testing stopped. Summing operation times for the flight profile test, the initial testing before the flight profile tests under this contract, and all testing done under Contract DA 44-177-AMC-294(T) indicated an estimated total exceeding 3000 hours accumulated on the feasibility system.

During the testing, the system had to be adjusted four times. The first two adjustments concerned the needle valve trim control, which had to be adjusted twice because it moved under vibration. This would not

happen in a production type system, because the trim would be fixed orifices installed at the factory. The final two adjustments were necessary because the filter had bypassed; therefore, the system twice had to be cleaned of contamination. This was a maintenance failure, which pointed out the need for suitable filtering.

From the preceding, the conclusion reached is that the hydraulic yaw damper system performed very well and demonstrated that a high level of reliability is possible.

CONCLUSIONS AND RECOMMENDATION

The results of this life test program support the reliability claims made for fluidics in the past and provide guidelines for other considerations in the field of fluidics.

- There are no catastrophic failure modes inherent in fluidic systems.
- Failures are not random as in electronics, but of a wearout mode.
- Environments do not increase the number of failures (other than those causing material damage).
- The vortex rate sensor can tolerate large amounts of contamination in the fluid.
- The vortex rate-sensor noise level is sensitive to manifolding.
- The vortex rate sensor, when utilizing oil, should incorporate a fixed blade to reduce null shifts and noise level.
- Hydraulic bistable amplifiers must, for practical applications, operate using other than the wall attachment effect.

The components and feasibility system performed as expected, in that they demonstrated a high reliability and tolerance for various grades of contaminated oil. There was no detectable material wearout trend.

Since none of the components failed, and since it was concluded that failure would come only as a result of wearout, it is recommended that a number of components, approximately five of each type, should be run for a number of years. If the components were checked only once every few months, a minimal manpower effort would be needed to conduct this type of test.

SECTION III
RELIABILITY EVALUATION

This section provides insight into the operational reliability and maintainability of fluidic components and systems through an evaluation of the test results. The evaluation will be in terms of the following parameters:

- Gross failure rates
- Mean-time-between-failure (MTBF)
- Failure modes
- Wearout performance degradation
- Mean-time-between-repair
- Repair time

GROSS FAILURE RATES (COMPONENTS)

Achieved

The failure rates achieved by the fluidic components as a result of the testing are considered to be "gross" failure rates, since statistically within the time limits of the test, they can only approximate the order of magnitude of the true failure rates of the fluidic components tested. Failure rates are divided into two categories: catastrophic and degradation.

Catastrophic Failure Rates

A catastrophic failure results in complete cessation of the intended component function. Thus, the catastrophic failure rate is applicable to catastrophic failures.

No catastrophic failures occurred during the component life testing, the system life testing, or the system flight profile simulation testing.

The three tests accumulated up to 3156 hours per component and totals of up to 55,859 hours per component type. Since failure rates are expressed in terms of failures per hour and are calculated using the equation, Failure rate = $\frac{\text{failures}}{\text{operating hours}}$, the achieved failure rate for zero failures is zero. The lack of

catastrophic failures was not totally unexpected. Engineering analysis of the components, coupled with past experience with fluidics, led to the hypothesis that catastrophic failure modes are not inherent in the fluidic components. The test results confirmed this hypothesis. The catastrophic failure rates of fluidic components are, therefore, expected to approach zero. These conclusions are entirely reasonable when the component designs, the type of materials used, and the absence of moving parts are considered.

Degradation Failure Rates

A degradation failure results in component performance outside of established performance limits. Thus, the degradation failure rate is applicable to degradation failures.

Degradation failures (failure rates) are of primary interest in the determination of component and system reliability for long-term useful-life application. The degradation failure, however, is not as readily identifiable as the catastrophic failure; therefore, major emphasis is placed on the development of component failure criteria for the test. The goal of this effort is to establish component failure criteria which could be meaningfully associated with a useful system-design application. This system-design association is necessary for the following two reasons:

- Arbitrarily chosen failure criteria may prove to be wholly inadequate when an attempt is made to apply them to a "real life" design.

- Component failure limits may be more or less stringent, depending upon in what type of system the component is used, or even upon how it is used in a particular system.

The Honeywell approach was to select specific damper system mechanizations as models for the establishment of system failure criteria. The final step was to equate the system failure criteria to component failure criteria by assessing the effects of component parameter variations on the overall system performance. Two systems were chosen for analysis. They were the feasibility model hydraulic yaw damper developed under Contract DA 44-177-AMC-294(T) and a future typical hydraulic damper system developed through in-house design studies following the completion of the feasibility program.

Three component parameters were chosen as representative of component performance with respect to degradation. These were:

- Scale factor (gain)
- Null
- Linearity

For most of the components, two failure limits were established for the above parameters to ensure the identification and study of those failure modes not already known and predictable. The first limit was based on the performance of the feasibility system and was used to indicate component degradation. The second limit was based on the predicted performance of the future typical system and was considered to be the point of component failure. The derivation of the failure limits is presented in Appendix II.

The first failure limit for null was exceeded early in the testing by both the rate sensors and the proportional amplifiers. The reason for the null shifts was not readily apparent and was tentatively attributed to a combination of the following factors:

- The feasibility nature of the devices
- Facility limitations
- Instrumentation and data analysis accuracy

The second failure limit was not exceeded in any parameter on the following devices:

- Rate sensor
- Proportional amplifier
- Bellows
- Trim control

These devices, therefore, completed the life testing with zero failures. All bistable amplifiers had parameter shifts which exceeded the second failure limits. However, the bistable amplifiers continued to operate as bistable devices throughout the testing. Because the bistable failure limits have no practical application meaning, no attempt was made to calculate degradation failure rates for the bistable amplifiers.

The conclusion reached is that the reliability (failure rates) of fluidic components cannot be evaluated using conventional reliability techniques. Component degradation does not conform to the exponential (Poisson) distribution with its associated random failures but, rather, the normal distribution associated with wearout effects. That is, no degradation failures are expected until the fluidic component life approaches the mean life of that

type of component and the device physically begins to deteriorate. Under these conditions, the component failure rate will remain at essentially zero until wearout occurs. The results of the component life testing conform to the theory that degradation is a wearout phenomenon.

Two problems associated with the wearout theory of fluidic component reliability are:

- Determining the mean life and the failure density distribution about the mean life.

- Evaluating data, life test or field operational, to determine an estimate of the failure rate when few or no failures have occurred and the mean life has not yet been determined.

The latter is the situation which confronts us in the case at hand.

The mean life of fluidic components is estimated to be high enough that wearout will not occur until a point in time beyond the expected useful life of the components (see Figure 1), giving a useful life-degradation failure rate of zero. However, it is desirable to have failure rates for fluidic components for use in making system reliability estimates, for estimating maintenance requirements, and for comparative analysis of fluidic and non-fluidic systems. Therefore, to provide a current best estimate of the fluidic component degradation failure rates achieved during the test, it will be assumed that degradation failures are exponentially distributed and that conventional reliability analysis techniques may be applied. The failure rates so derived are presented in Table II along with the achieved or demonstrated failure rates of zero. The achieved rates are failures/hour. The Poisson rates are failures/hour with 0. 7 failure assumed (50 percent confidence level) for zero failures. It should be noted that the failure rates are a function of the number of test hours and the number of failures experienced. Confidence increases with hours and failures.

MEAN-TIME-BETWEEN-FAILURE (MTBF) SYSTEM

Achieved

System Testing

The fluidic yaw damper system accumulated a total of 1912 operating hours without a chargeable failure during the flight profile simulation and life tests. Using standard reliability equations,

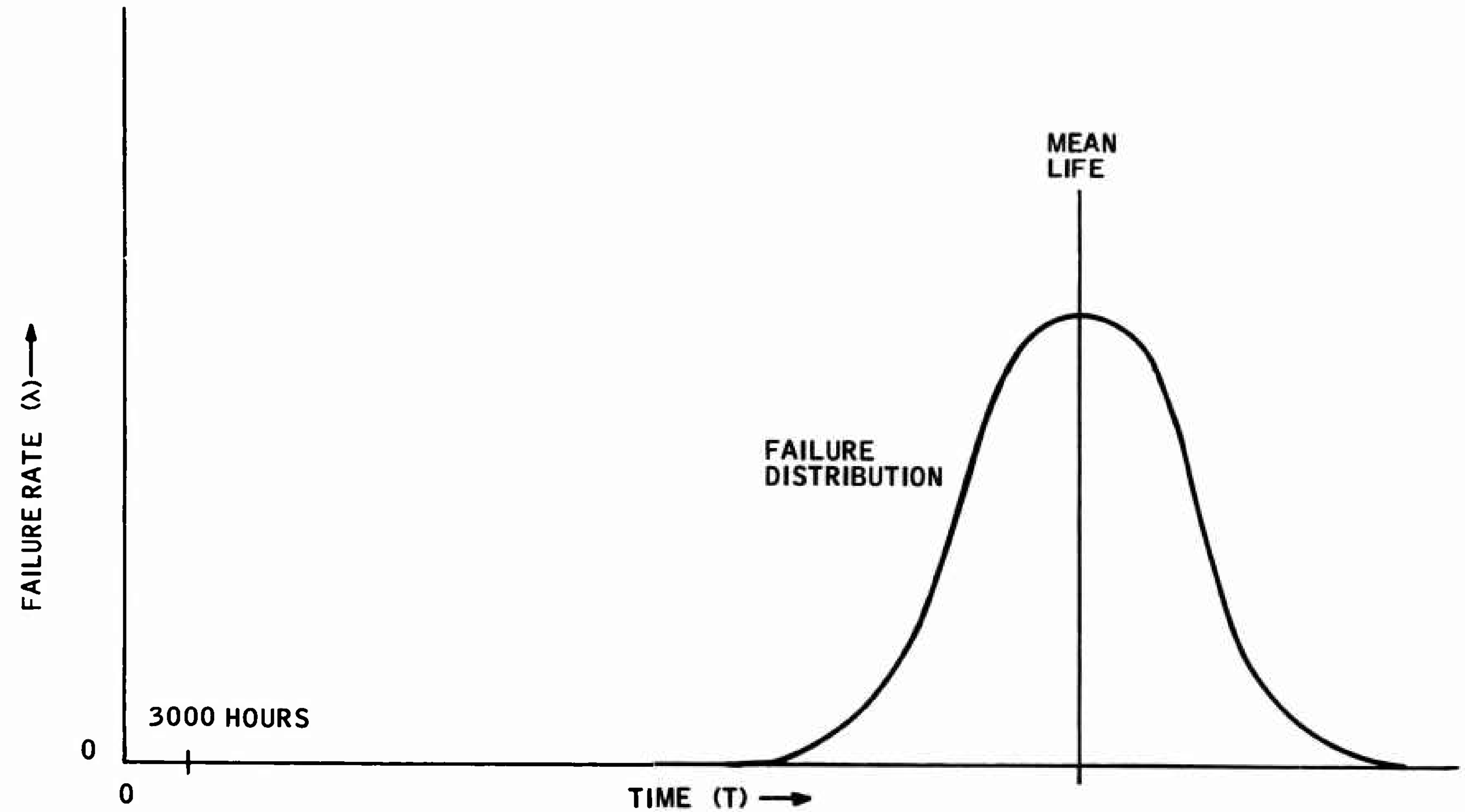


Figure 1. Wearout Failure Distribution.

TABLE II. ACHIEVED COMPONENT DEGRADATION FAILURE RATES

Component	Operating Hours	Failures	Failure Rate - Best Estimate: Achieved %/1000 Hours	Failure Rate - Best Estimate: Poisson Distribution %/1000 Hours
Sensor	48,466	0	0	1.44
Proportional Amplifier	55,859	0	0	1.25
Bellows	49,164	0	0	1.42
Trim Control	44,890	0	0	1.56

$\text{MTBF} = \frac{\text{Hours}}{\text{Failures}} = \frac{1912}{0}$, gives an undefinable value, or a MTBF of at least 1912 hours. There were no signs of performance degradation; therefore, the system life and MTBF are expected to be much higher than is shown by the testing conducted to date. This presents the problem of attempting to estimate the true system MTBF. If it is assumed that system degradation failures are randomly distributed (exponential distribution), the standard reliability techniques can be applied. Thus, the 1912 hours of test experience will give a best estimate of MTBF of 2730 hours. It should be again noted that this MTBF figure is a function of, and limited by, the number of test operating hours, and the only way of demonstrating a higher MTBF is through accumulation of thousands of hours of operating experience.

An important facet of fluidics, which was demonstrated during the system (and component) testing, is its immunity to environmental changes as discussed in the preceding section on components. This is important from the viewpoint of reliability because it indicates that laboratory test experience can be related to aircraft or field operations without the use of application factors. Reliability numbers (MTBF, failure rate, etc.) which are generated via laboratory testing may be considered to be field achievable.

Synthesized System Testing

To further evaluate the system aspects of the test program, seven systems were synthesized from the life test components. The systems consisted of one rate sensor and two proportional amplifiers, the gain components of the future typical system. The systems were selected by component number with the selection order determined with the aid of a random numbers table. The scale factor (gain) was selected as the parameter which was most representative of system performance. The change in scale factor, from the initial value, for each of the components was then plotted for each system. The calculated system gain changes were superimposed on the same graphs to show the combined effect of the three component gain changes. These graphs are presented in Figures 2 through 8. All synthesized system scale factor changes were within the system failure limits of ±36.0 percent change from the initial value. The average change for all data points for the seven systems was 6.9 percent. The maximum change at an individual data point was 27.0 percent.

The synthesized systems accumulated a total of 24,686 hours without failure. If this time is then combined with the actual system testing, a total of 26,598 hours and zero failures were accumulated. This experience gave a best estimate of the achieved MTBF of 37,997 hours.

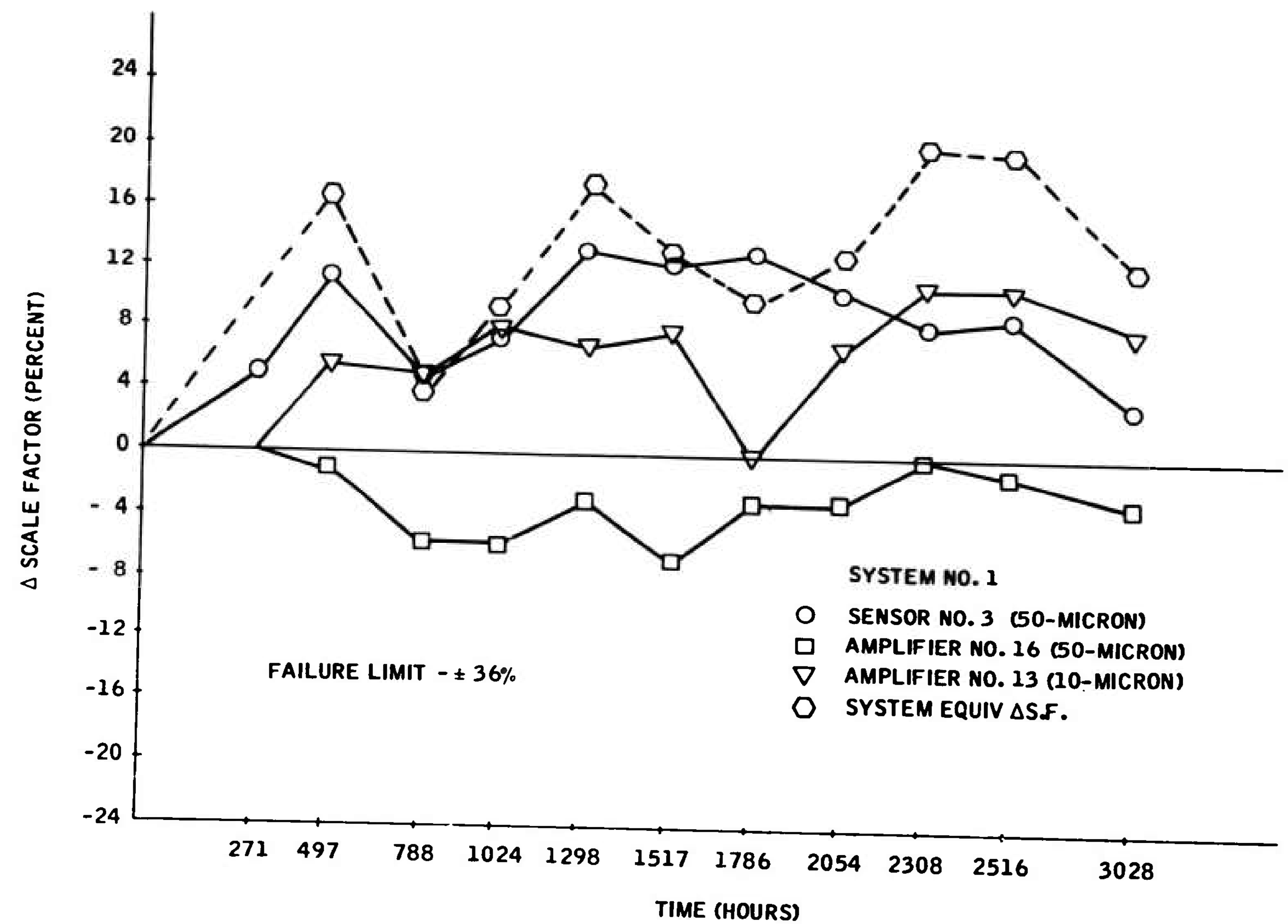


Figure 2. Equivalent System No. 1 Performance - Scale Factor.

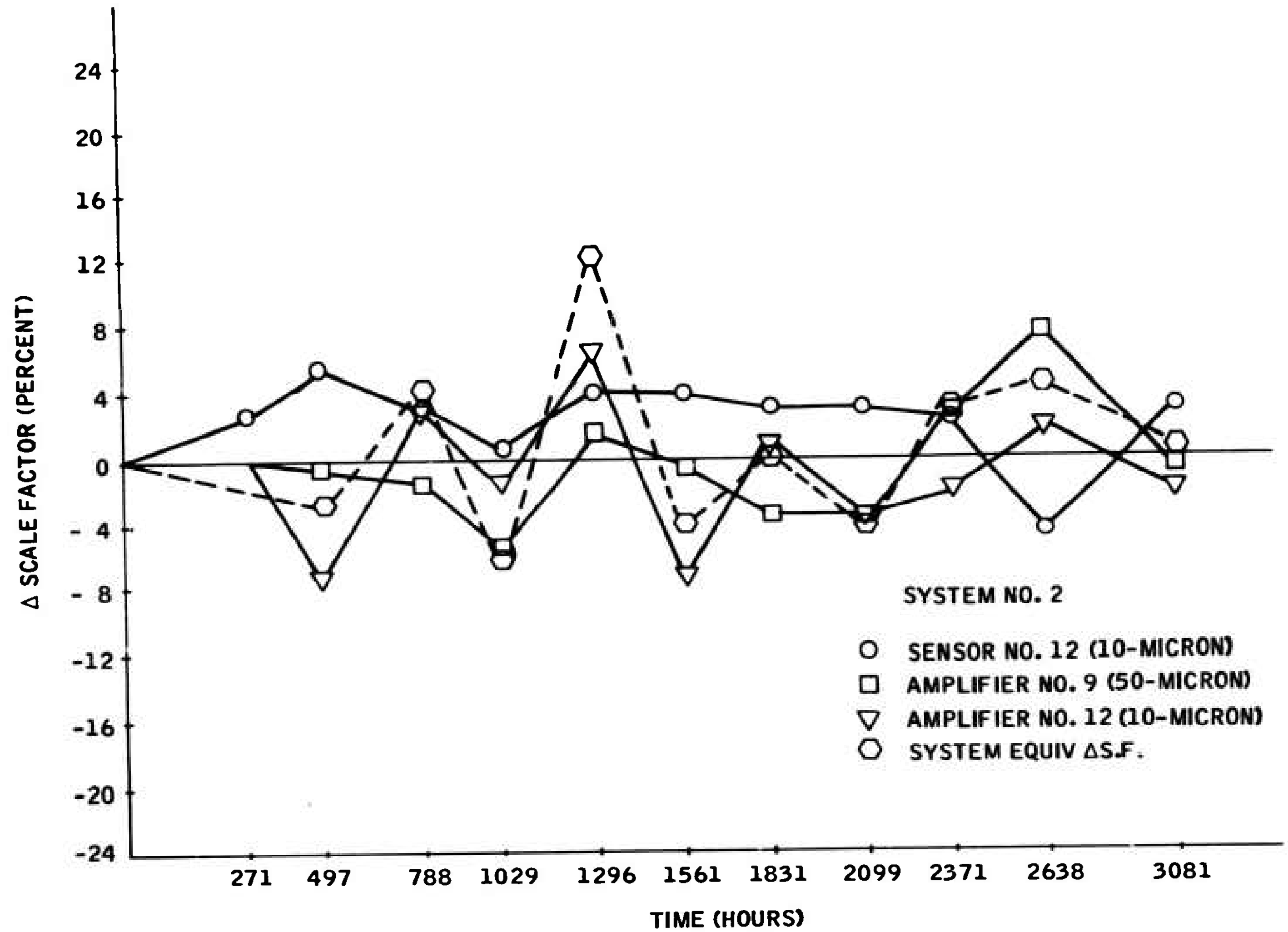


Figure 3. Equivalent System No. 2 Performance - Scale Factor.

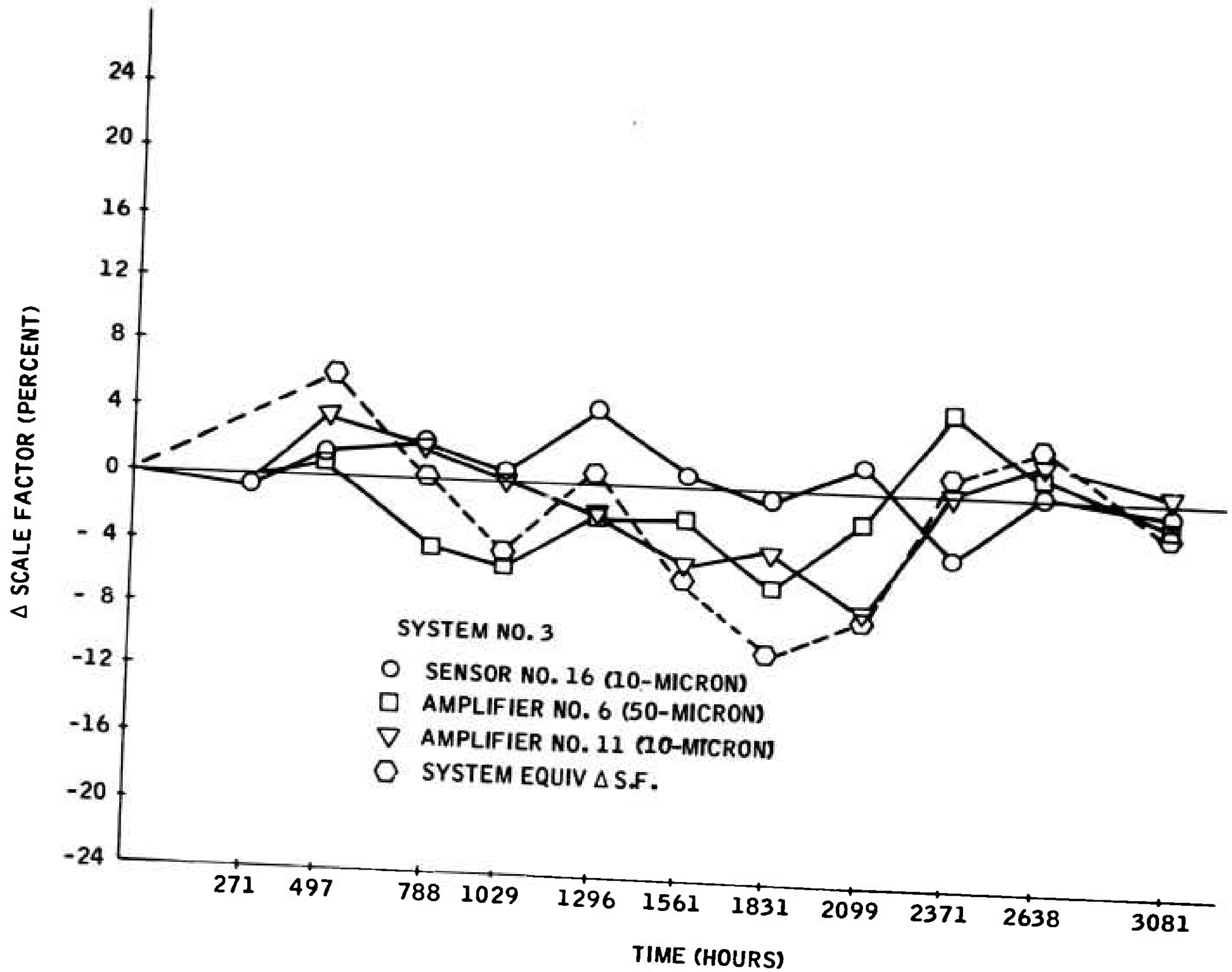


Figure 4. Equivalent System No. 3 Performance - Scale Factor.

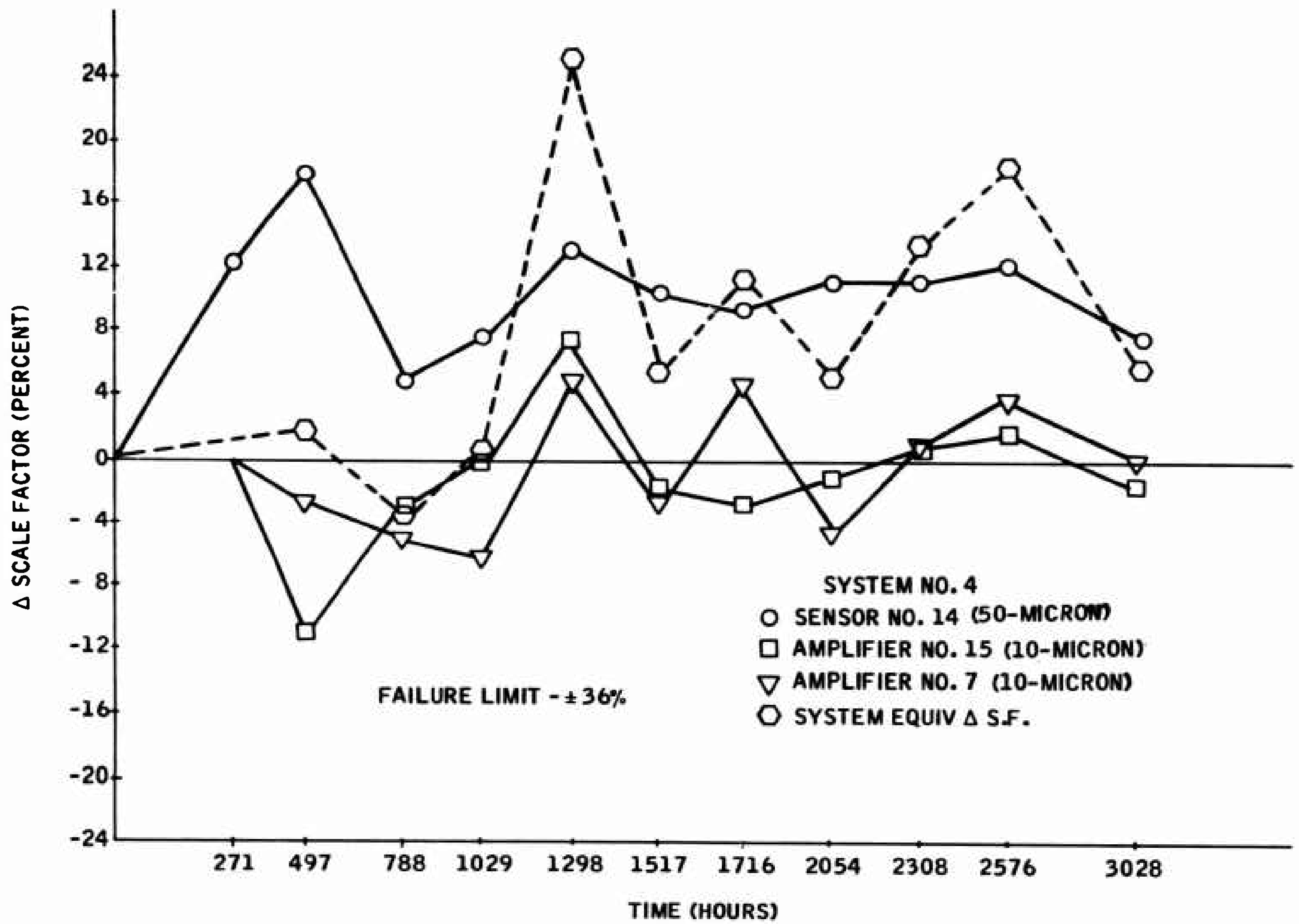


Figure 5. Equivalent System No. 4 Performance - Scale Factor.

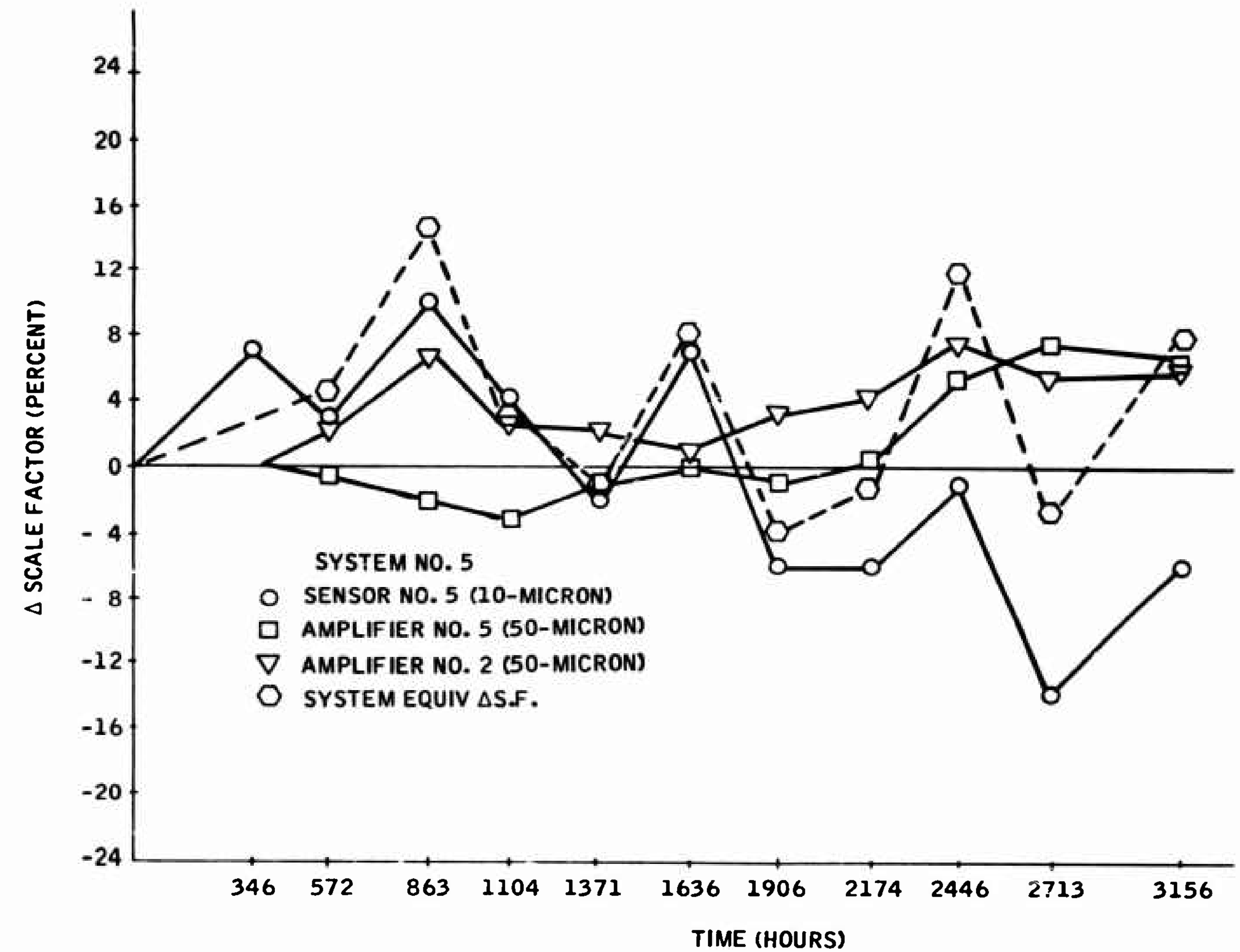


Figure 6. Equivalent System No. 5 Performance - Scale Factor.

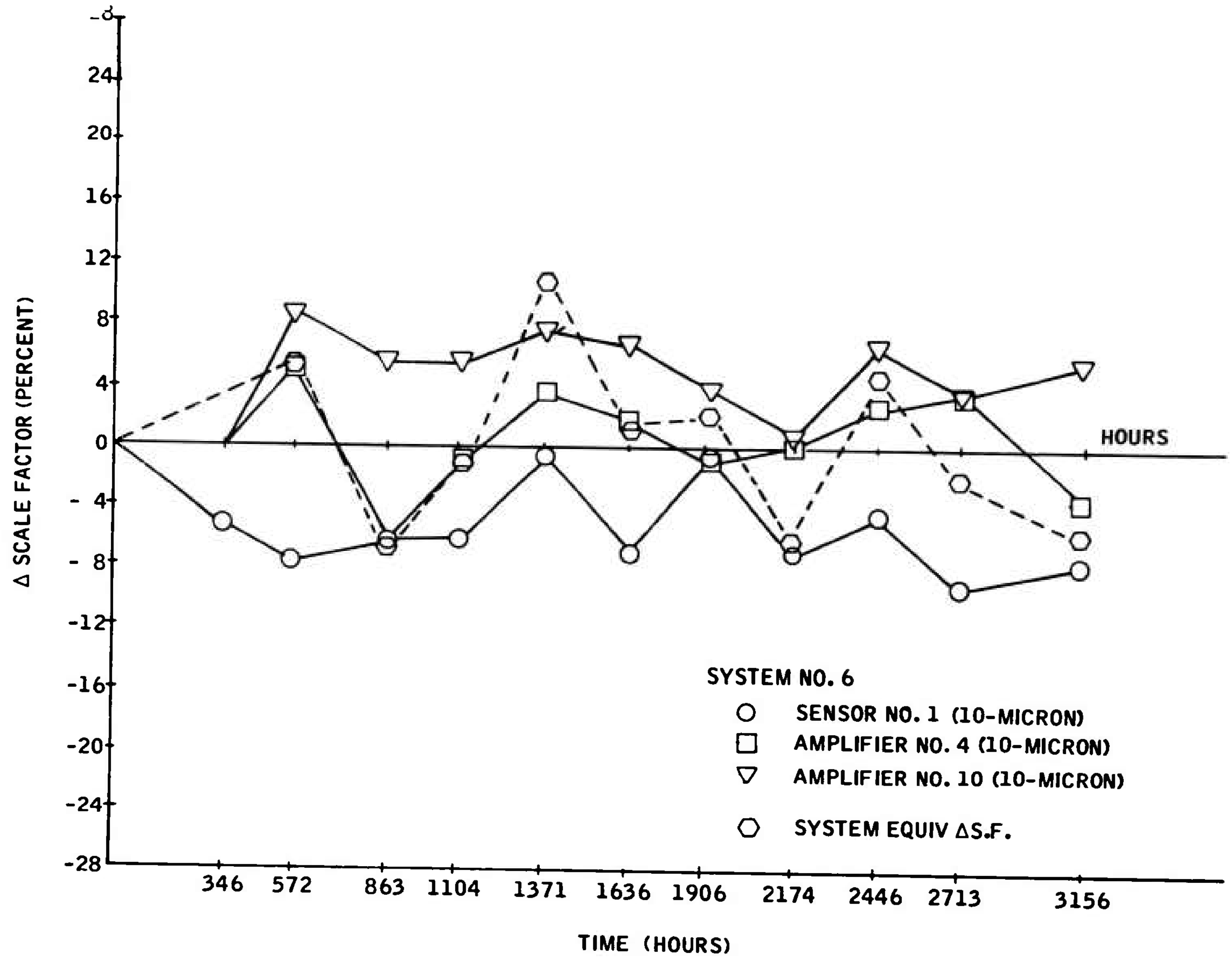


Figure 7. Equivalent System No. 6 Performance - Scale Factor.

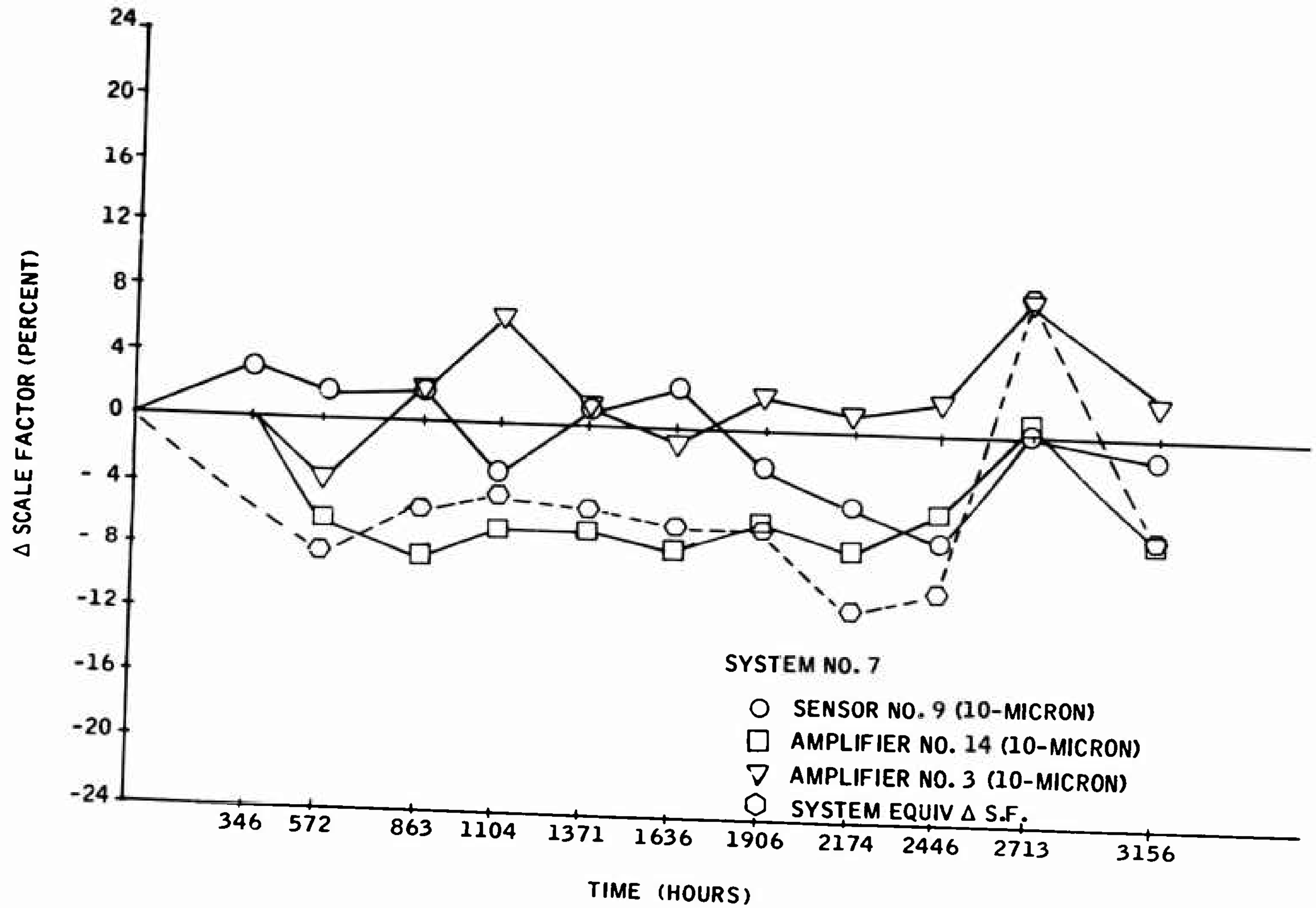


Figure 8. Equivalent System No. 7 Performance - Scale Factor.

Comparison of Electromechanical and Fluidic Damper Systems

System schematics of the electromechanical and fluidic yaw dampers used for this comparison are shown in Figures 9 and 10 respectively. The predicated MTBF's for these systems are 9000 hours for the electromechanical system and 83, 000 hours for the fluidic system. These MTBF's are developed in Tables III and IV. The electronic component failure rates are Honeywell rates which are applicable to aircraft systems. The fluidic component failure rates are Honeywell projected rates from Table V.

The projected failure rates were derived mainly through the development of analogies between fluidic and pneumatic components and hydraulic and hydromechanical components, and applying available failure rates from these components to the fluidic components. They were developed because it is desirable to be able to estimate the potential reliability of fluidic components or systems without waiting for reliability to be proved by test and/or operational experience. Demonstrating reliability (failure rates) to the level expected of fluidic components will require millions of test and/or operational experience hours, whether considering wearout or random failures.

The confidence that Honeywell has in the soundness of the philosophy of projected failure rates and in the reasonableness of the numbers selected is not based entirely on the subject test program. Previous fluidic programs have supplied, and are now supplying, data on both the operational life and the failure rates of fluidic components. Fluidic logic elements have accumulated 1, 450, 000 field-operation hours with operating times up to 10, 600 hours in a high-vibrational environment without failure. This gives a best-estimate failure rate of 0. 048 percent/1000 hours. A proportional and a bistable amplifier have each been operating for over two years (18, 700 hours) on unfiltered shop air without failure. Admittedly, these devices are different than those tested in this program, and the operating environments are different. However, data such as this is the start of a data accumulation which will eventually prove that fluidic devices are indeed as reliable as they are now predicted to be. More specifically, the data generated by this fluidic reliability program and the other programs mentioned serve to demonstrate that fluidic devices and systems have advanced to where they may now be applied with confidence to aircraft systems.

In addition to the obvious MTBF advantage, the fluidic damper has other less apparent advantages over the electromechanical damper. The first concerns the potential MTBF in the helicopter environment. The Honeywell failure rates are known to be applicable without application factors in general aircraft environments, and the same assumption is made for the helicopter environment. However, the helicopter environment may adversely affect the rate gyro, an effect expected to increase

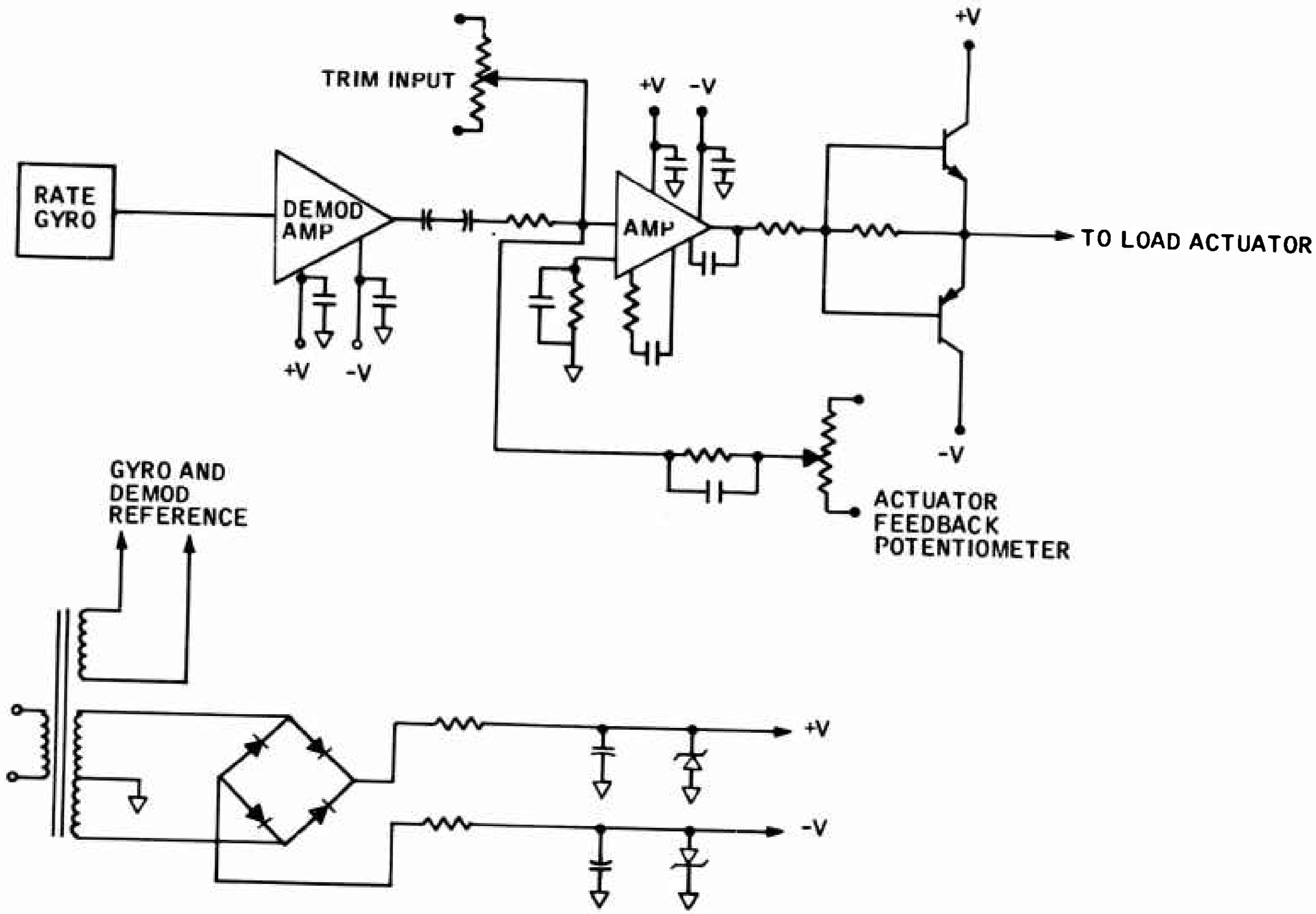


Figure 9. Electromechanical Yaw Damper.

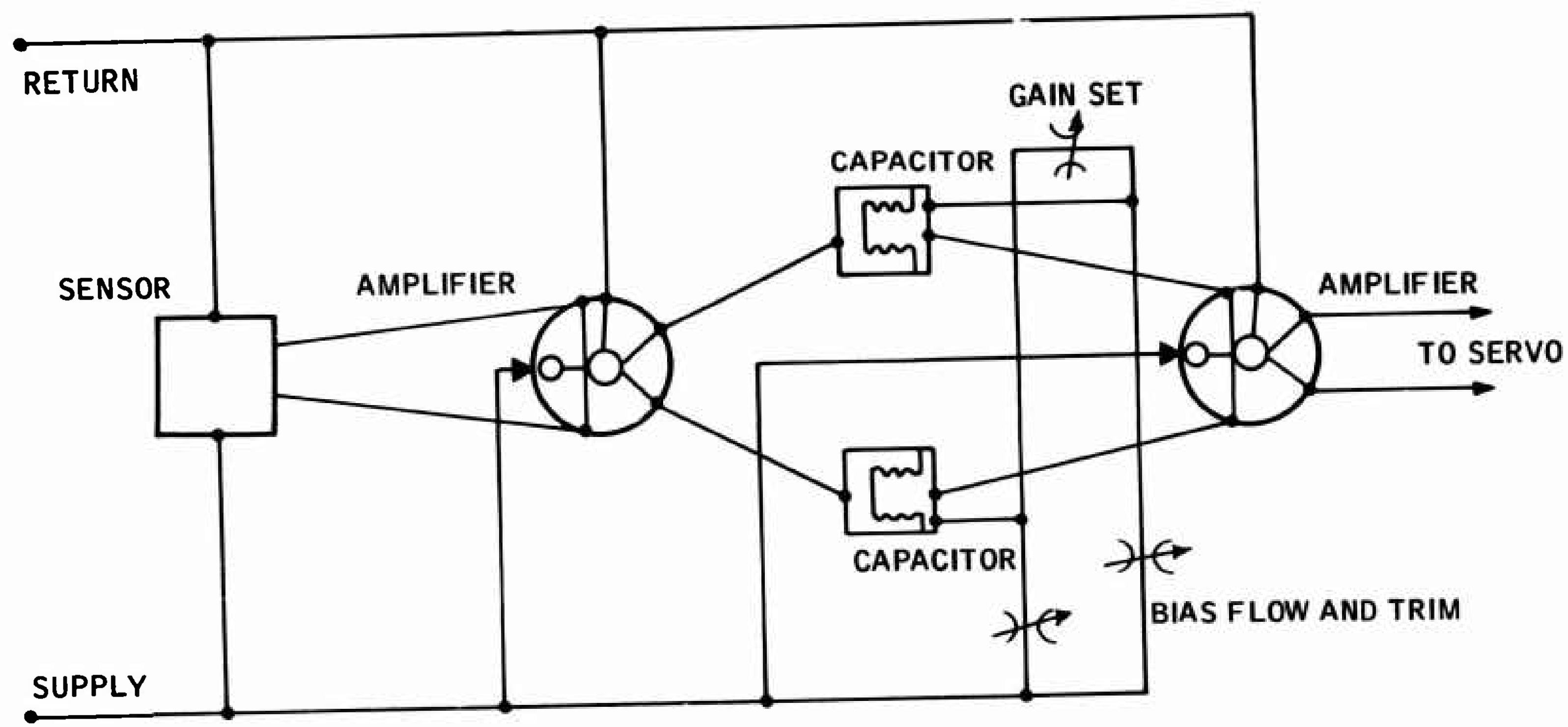


Figure 10. Fluidic Yaw Damper.

TABLE III. RELIABILITY PREDICTION - ELECTROMECHANICAL YAW DAMPER

N	Component	λ %/1000 Hours	$N\lambda$ %/1000 Hours
15	Capacitor, Tantalum	0.023	0.345
4	Diode	0.023	0.092
2	Diode, Zener	0.020	0.040
1	Gyro, Rate	10.000	10.000
2	Integrated Circuit, Linear	0.006	0.012
2	Potentiometer	0.166	0.332
5	Resistor, Carbon Comp.	0.002	0.010
9	Resistor, Metal Film	0.014	0.126
1	Transformer, Power	0.181	0.181
			$\lambda_T = 11.138$

$$\text{MTBF} = \frac{1}{\lambda_T} = \frac{10^5}{11.138} = 9000 \text{ Hours}$$

TABLE IV. RELIABILITY PREDICTION - FLUIDIC YAW DAMPER

N	Component	λ %/1000 Hours	$N\lambda$ %/1000 Hours
2	Amplifier, Proportional	0.05	0.10
2	Capacitor, Fluidic (Bellows Type)	0.10	0.20
27	Interconnections	0.002	0.054
1	Sensor, Rate	0.10	0.10
3	Valve, Adjust	0.25	0.75
			$\lambda_T = 1.204$

$$\text{MTBF} = \frac{1}{\lambda_T} = \frac{10^5}{1.204} = 83{,}000 \text{ Hours}$$

TABLE V. PROJECTED FLUIDIC COMPONENT FAILURE RATES	
Fluidic Component	λ %/1000 Hours
Amplifier, Bistable	0.05
Amplifier, Proportional	0.05
Capacitor, Fluidic (Bellows Type)	0.10
Interconnection	0.002
Sensor, Rate	0.10
Valve, Adjust (Variable Orifice)	0.25

the failure rate. That is, there is a high probability that the actual electromechanical damper MTBF will be lower, rather than higher, than the predicted MTBF. The fluidic damper MTBF, however, will not change if the helicopter environment is worse than expected. The second factor concerns maintainability. The electromechanical damper has components which have a limited life and require scheduled maintenance.

The preceding discussions show, from both a reliability and a maintainability viewpoint, that the fluidic yaw damper is superior to the electromechanical yaw damper as used in the helicopter environment.

FAILURE MODES

Catastrophic

The catastrophic type of failure, which can cause almost instantaneous loss of system performance, did not appear as a failure mode during the fluidic system and component testing.

The only two types of failures which could conceivably be considered as catastrophic, and both would result from an external cause, are:

- Blocking of a passage, port, or nozzle by a large piece of contaminant
- Rupturing of a supply or signal line

However, neither of these hypothetical failures has a very high probability of occurrence. The first failure is prevented by fluid supply filtering, while the second is prevented by using proper design and packaging techniques.

The conclusion reached is that the probability of a catastrophic failure occurrence in a fluidic system is so low that the catastrophic failure may be considered to be a nonexistent failure mode for all normal fluidic system operating conditions.

Parameter Shifts

Parameter shifts, as expected, were experienced on all devices. However, they were generally less than the established failure limits and did not display a trend. The observed parameter shifts included the instrumentation reading and data analysis errors; therefore, the actual parameter shifts were probably less than those indicated. Table VI lists the average and maximum observed component parameter shifts. Table VII lists the maximum observed system parameter shifts during the flight profile and life testing phases. For comparison purposes, the allocated failure limits for the performance parameters are also listed. The derivation of the system failure limits and an explanation of their relationship to the components is presented in Appendix II.

WEAROUT-PERFORMANCE DEGRADATION WITH TIME

Wearout or performance degradation with time was not observed during the component testing. Analysis of the life test component performance parameter data confirmed this conclusion. That is, no parameter shifts were introduced as a result of the exposure to the test environments. These environments included device ambient temperature ycling, fluid temperature cycling, vibration, continuous input cycling, and two levels of hydraulic fluid contamination.

The average change from the initially measured value was plotted for all component parameters for which failure limits were assigned. The maximum positive and maximum negative changes from the initial value were also plotted for each data point (performance test). These plots

TABLE VI. OBSERVED COMPONENT PARAMETER SHIFTS

Component	Performance Parameter	Average Shift (%)	Maximum Shift (%)	Failure Limit (%)
Sensor	Scale Factor	± 2.0	18.0	±20.0
	Linearity	± 0.5	7.0	±10.0
	Null	± 3.6	26.0	±30.0
Proportional Amplifier	Scale Factor	± 2.4	10.5	±20.0
	Linearity	± 1.0	7.5	±10.0
	Null	± 5.5	25.0	±30.0
Bellows	Deflection (Scale Factor)	± 2.2	10.5	±20.0
Trim Control	Null	± 6.0	30.0	±90.0
Bistable Amplifier	Pressure Gain	±18.0	180.0	±25.0
	Null	± 0.5	3.7	± 1.0

TABLE VII. OBSERVED SYSTEM PARAMETER SHIFTS

System	Performance Parameter	Maximum Shift	Failure Limit
Flight Profile Test	Amplitude Ratio	31.4%	±36.0%
	Scale Factor	24.5%	±36.0%
	Linearity	4.5%	±15.0%
	Null	0.025 in.	± 0.075 in.
	Phase Angle	36 deg Max	50 deg Max
Life Test	Amplitude Ratio	34.0%	±36.0%
	Scale Factor *	- -	±36.0%
	Linearity *	- -	±15.0%
	Null *	- -	± 0.075 in.
	Phase Angle	40 deg Max	50 deg Max

*System not checked in shorted hi-pass condition

are Figures 11 through 20. No trends were apparent in any of the parameters, either average or maximum curves, for any of the components. It was this absence of trends which allowed the conclusion that there was no performance degradation during the testing.

MEAN-TIME-BETWEEN-REPAIR

The mean-time-between-repair (MTBR), or more appropriately, mean-time-between-maintenance-actions, is an important factor in evaluating a system, because it (and repair time) determines the maintenance effort associated with a particular system. A system which derives its reliability at the expense of high maintenance may provide less system, and thus aircraft, availability than one with a lower reliability but less total maintenance.

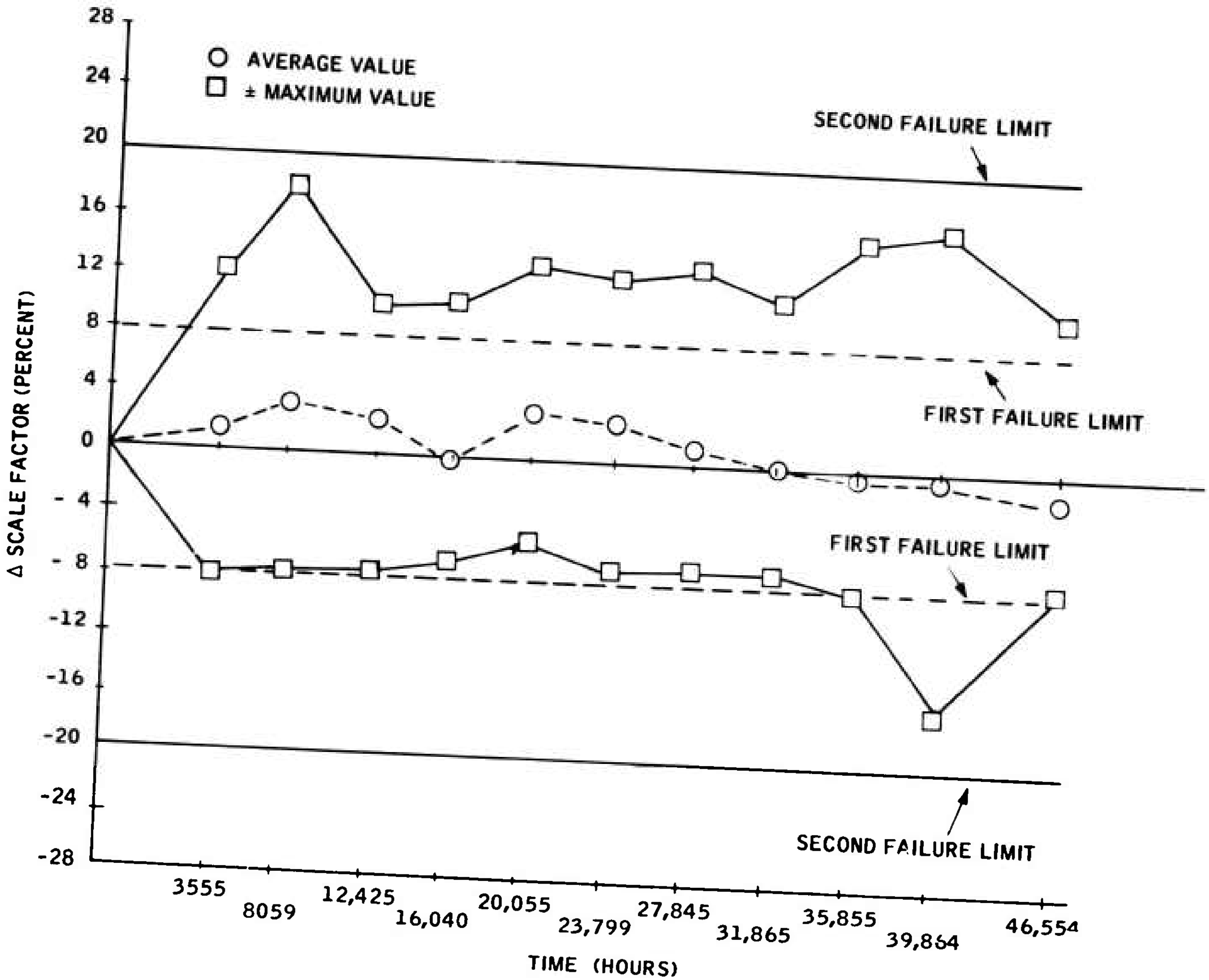


Figure 11. Rate Sensor Performance - Scale Factor.

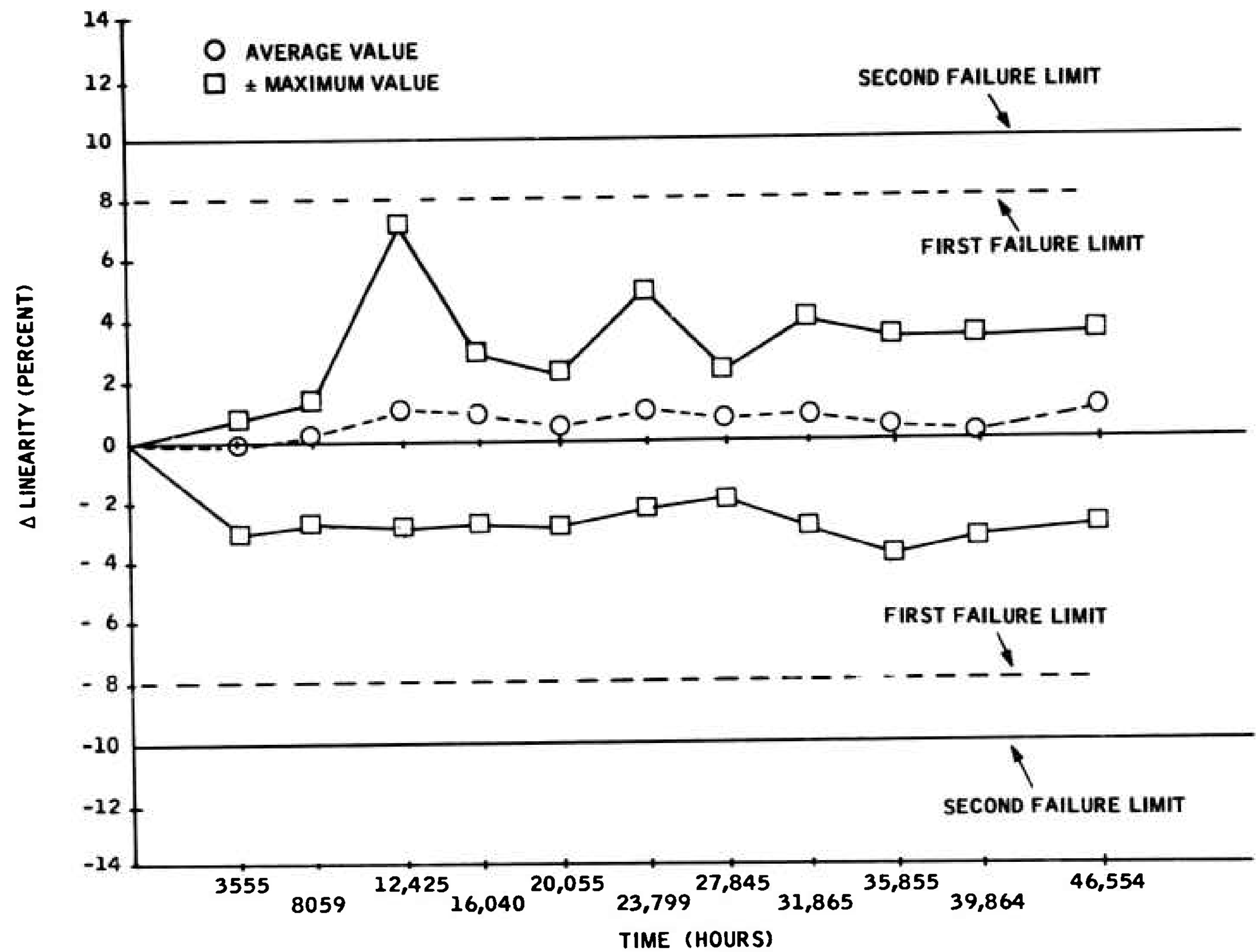


Figure 12. Rate Sensor Performance - Linearity.

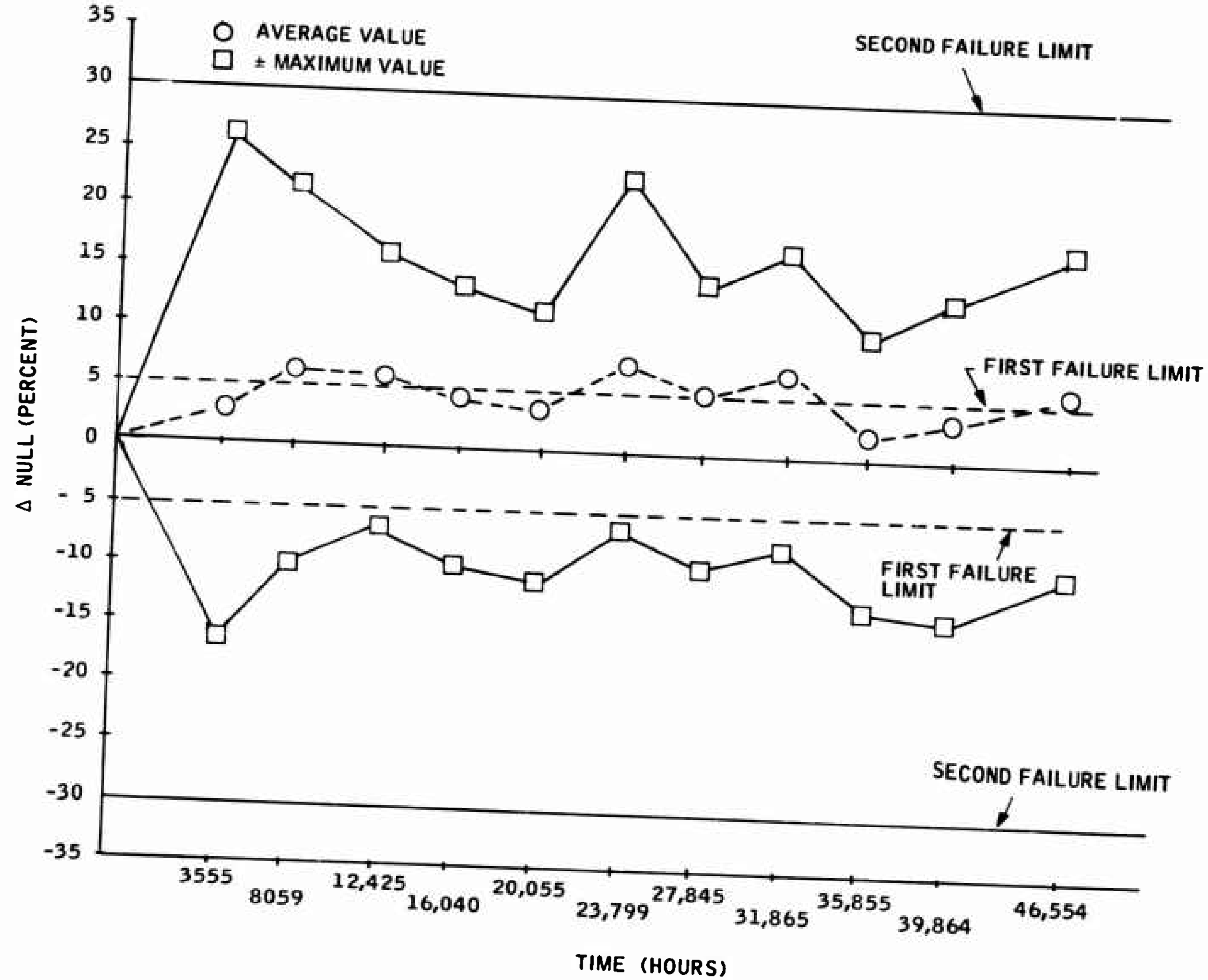


Figure 13. Rate Sensor Performance - Null.

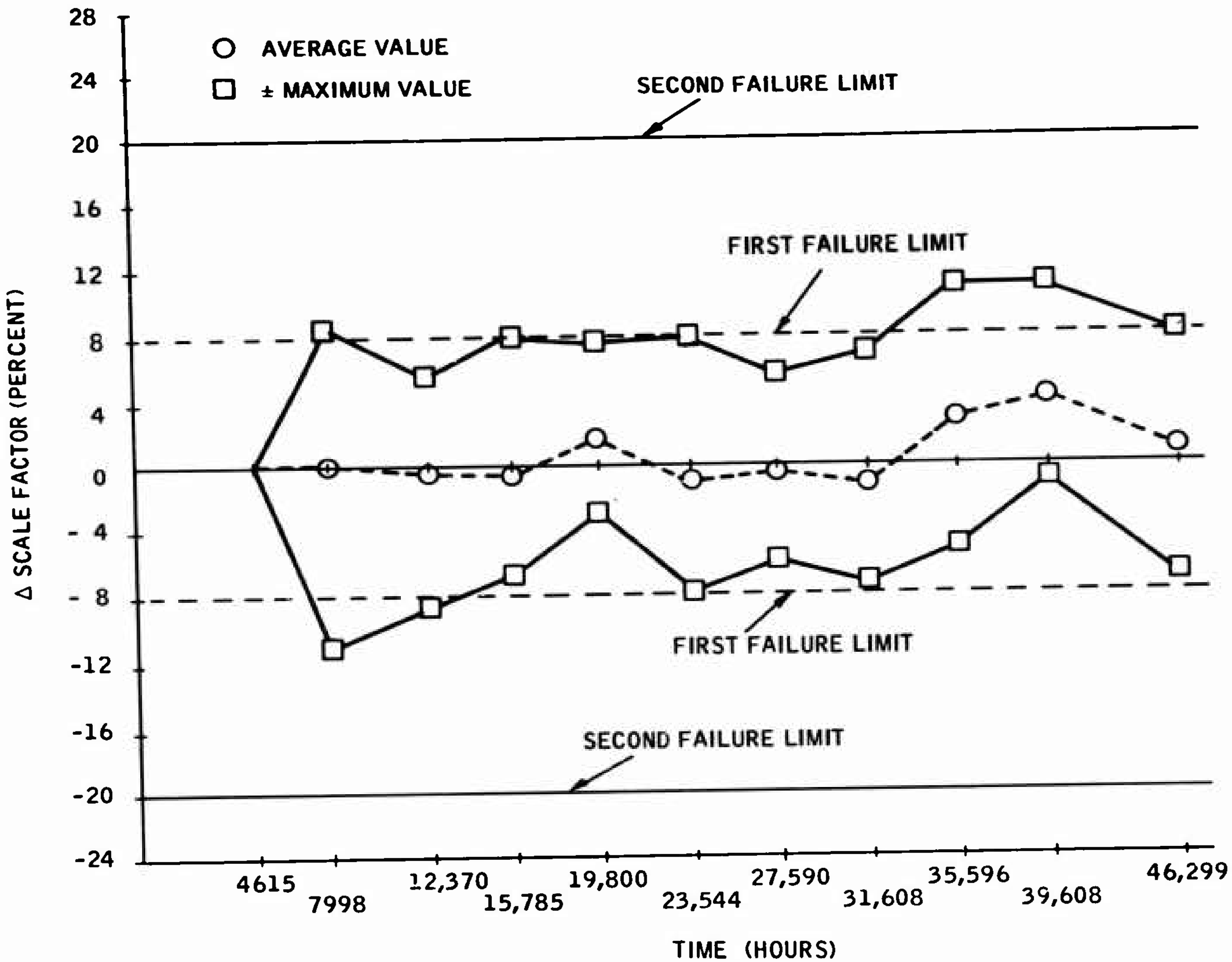


Figure 14. Proportional Amplifier Performance - Scale Factor.

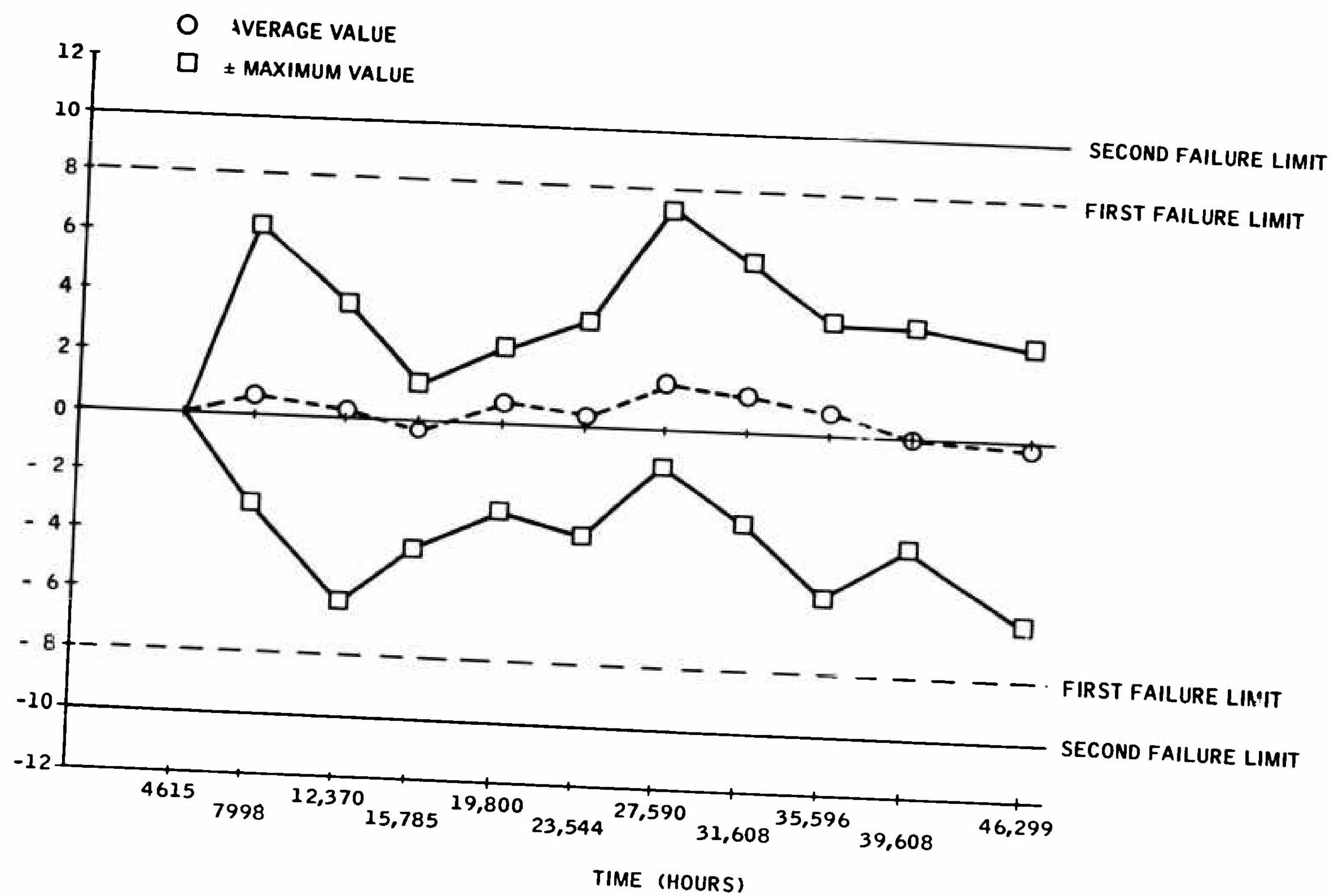


Figure 15. Proportional Amplifier Performance - Linearity.

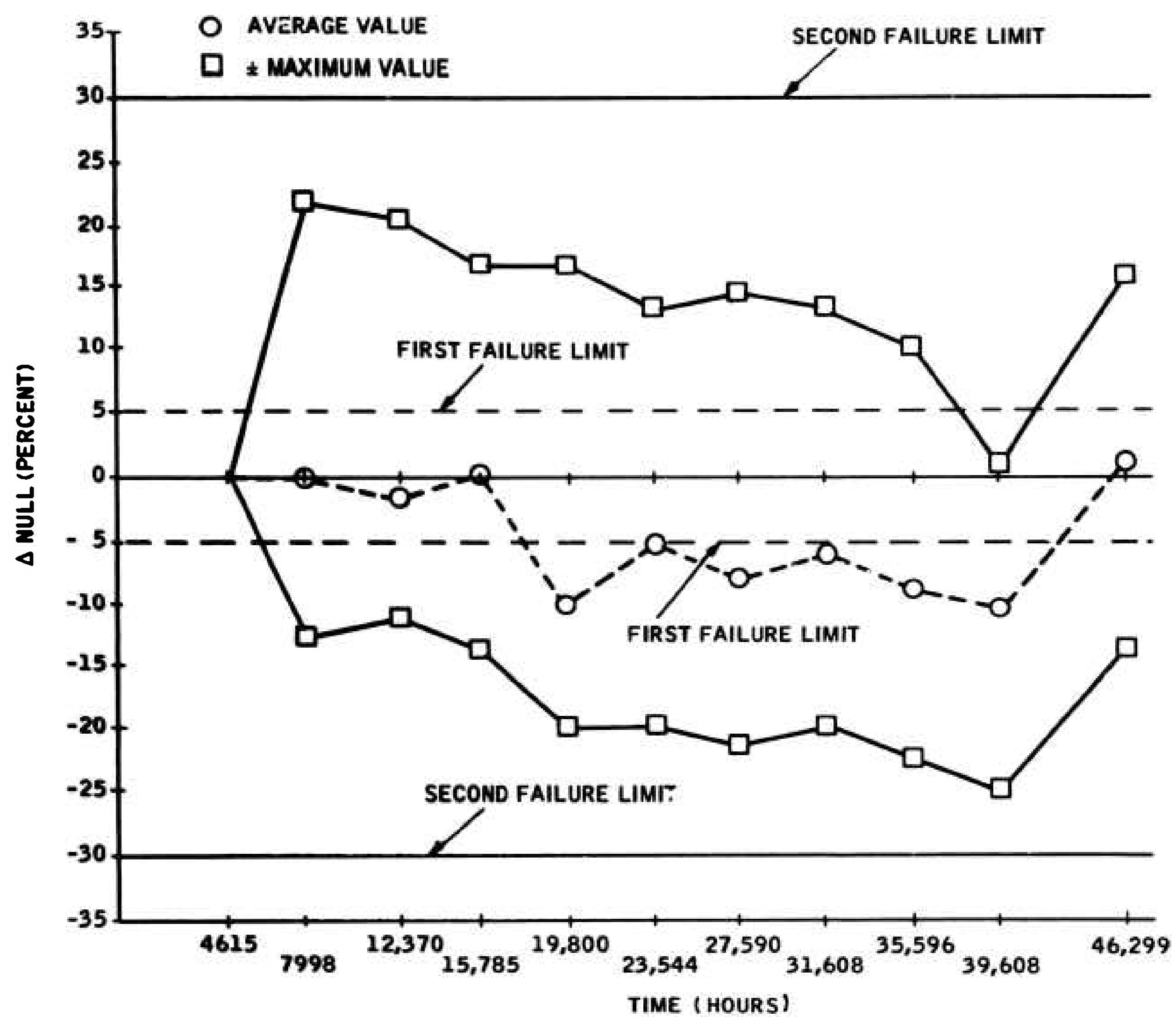


Figure 16. Proportional Amplifier Performance - Null.

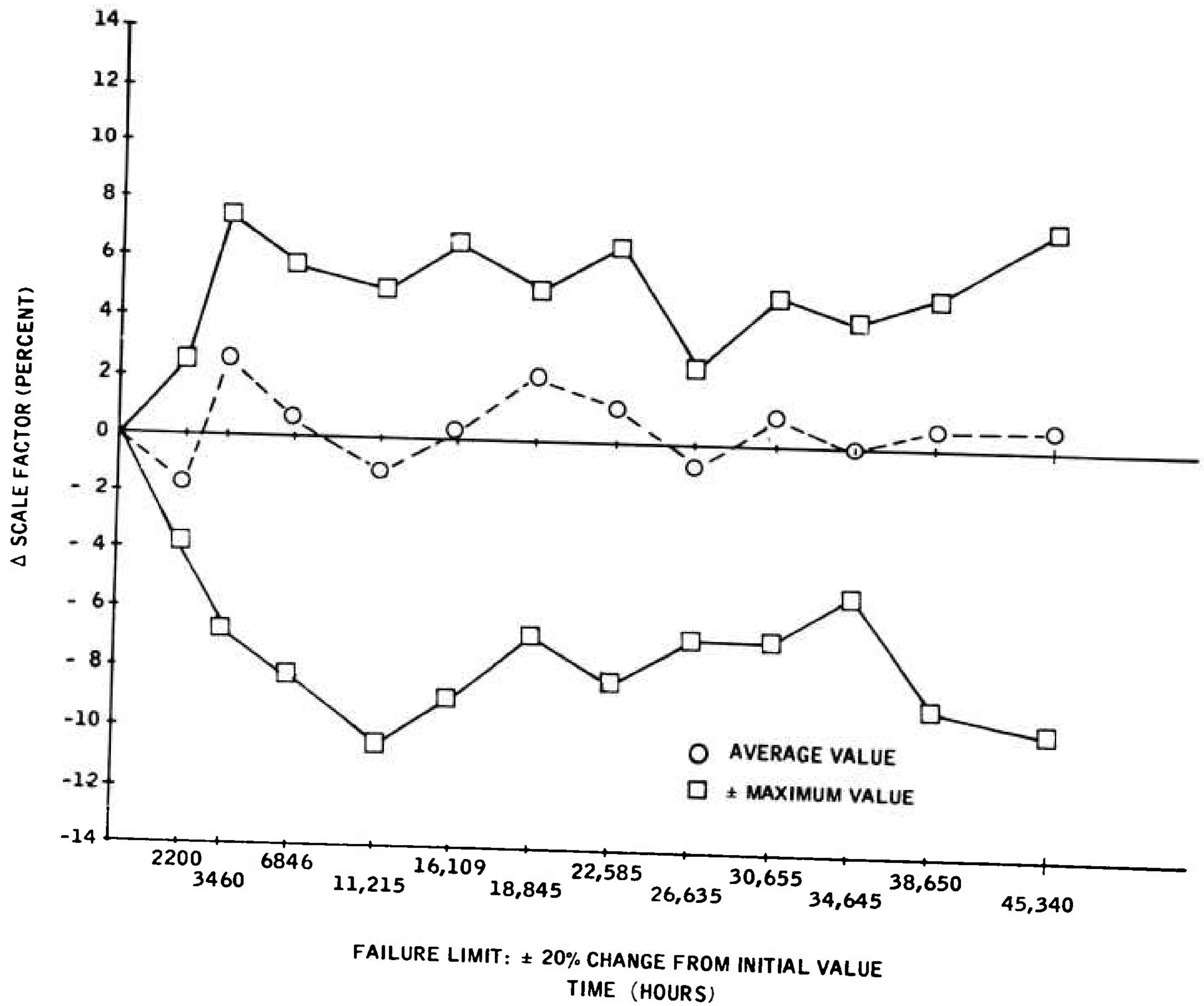


Figure 17. Bellows Performance - Scale Factor.

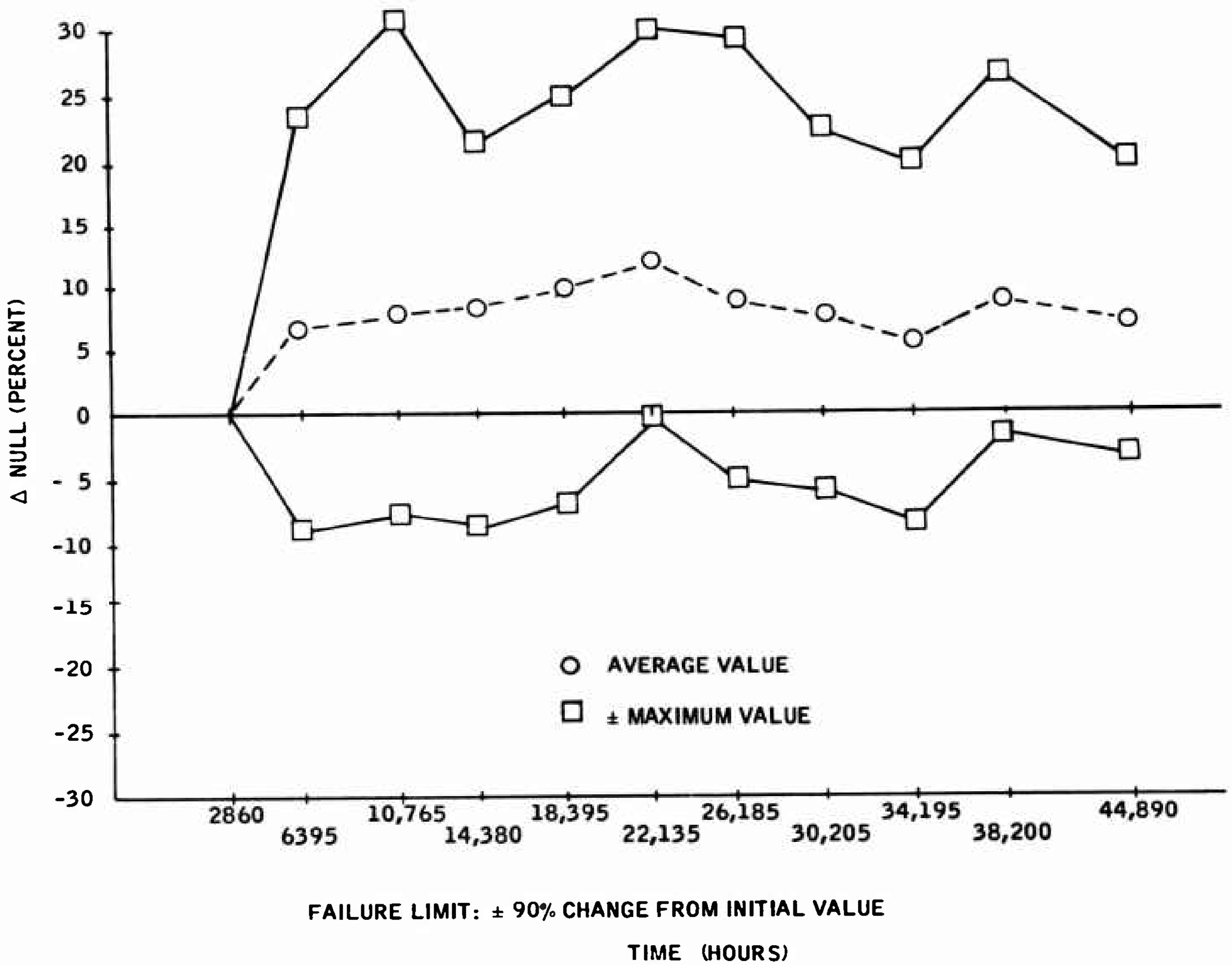


Figure 18. Trim Control Performance - Null.

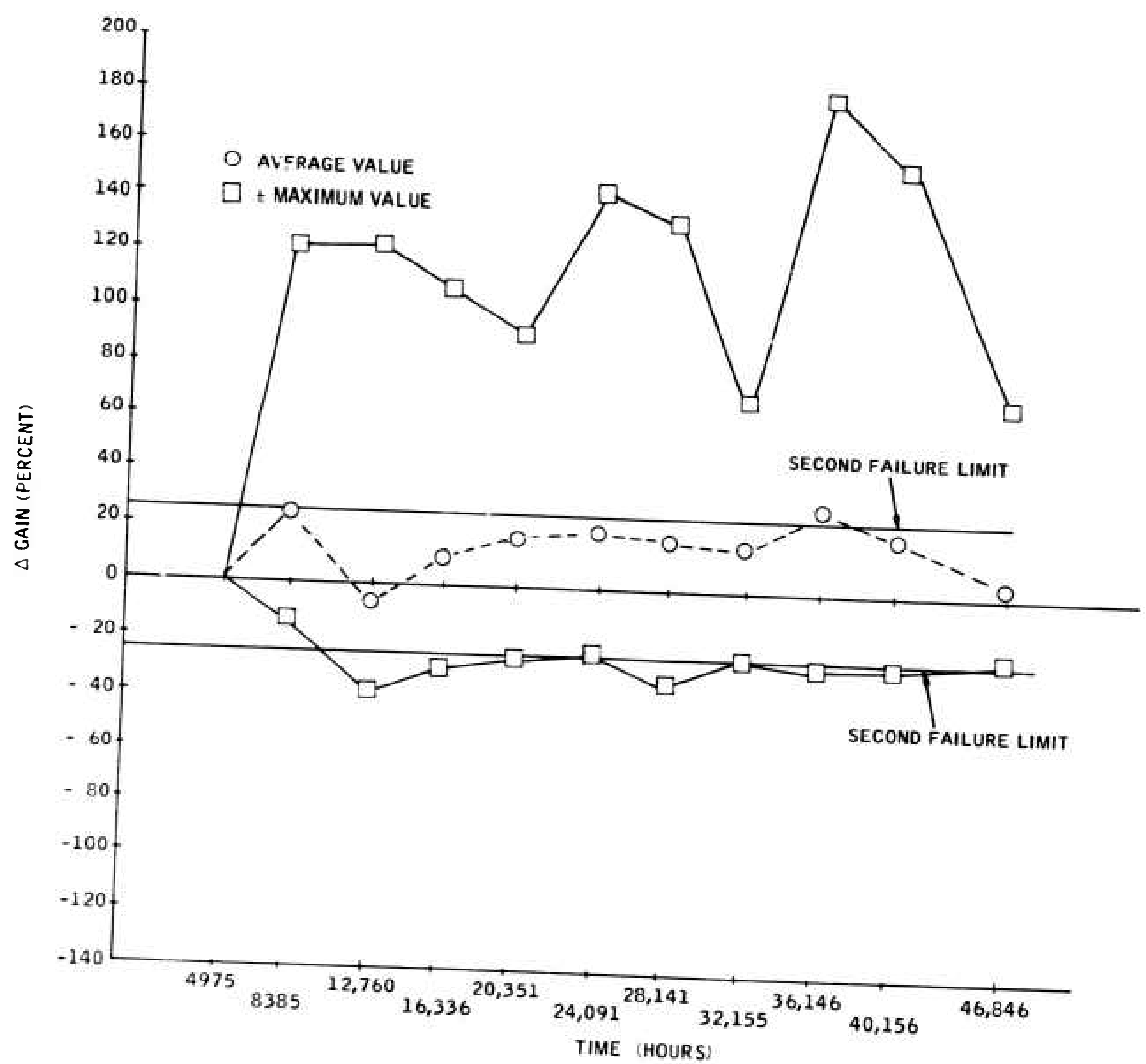


Figure 19. Bistable Amplifier Performance - Gain.

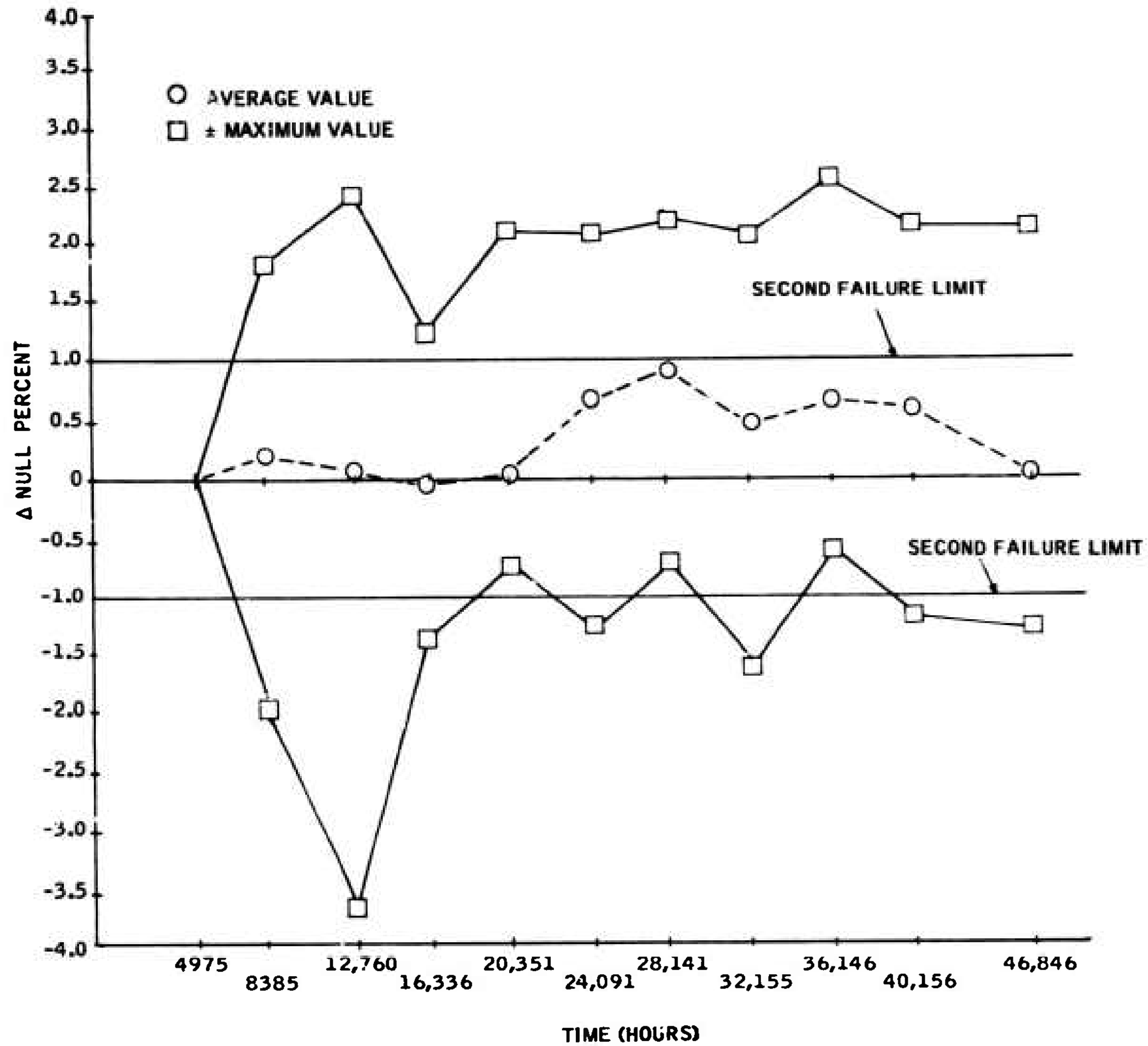


Figure 20. Bistable Amplifier Performance - Null.

The fluidic system, however, combines high reliability with low maintenance and will therefore provide a high level of aircraft availability. The fluidic system will require no scheduled maintenance and possibly no maintenance at all (scheduled or unscheduled) for the life of the system or aircraft.

The electromechanical system does have components which will require scheduled maintenance. The gyro has a mean life of 3000 to 4000 hours and would have to be replaced at least that often. The feedback potentiometer may require periodic cleaning or replacement.

The electromechanical yaw damper system can be expected to have a mean-time-between-maintenance-actions of 3000 to 4000 hours. The fluidic yaw damper system can be expected to have a mean-time-between-maintenance-actions of 80,000 hours. It is evident that the fluidic system will require far less (approximately 1/20) maintenance effort than an equivalent electromechanical system.

REPAIR TIME

Fluidic system and/or component repair time was not determined, as the minimal number of failures which occurred during all phases of the reliability test program afforded insufficient opportunities for gaining the repair experience needed to make such a determination. Therefore, only estimated repair times can be given. An average repair time in the range of two to four hours is estimated for a fluidic system of the complexity of the yaw damper system. Both the feasibility and future systems were used as models for this estimate, which is predicated on the assumption that the individual components will be "throw-away" items and repair will consist of fault isolation and component replacement. Repair time for a fluidic system will probably be higher than that for an equivalent electromechanical system, but this should be more than offset by the fewer number of repairs required by the fluidic systems, 1/20 as many as the electromechanical system.

SECTION IV

TECHNICAL EVALUATION

INTRODUCTION

This section concerns the design, fabrication, and test of the individual components, hydraulic damper system, and the life test fixturing. Also discussed are the problems encountered and conclusions and recommendations that are a direct outcome of this program.

COMPONENTS

Five types of components were subjected to a 3000-hour life test. They were vortex rate sensors, proportional amplifiers, capacitor bellows, trim controls, and bistable amplifiers. These are shown in Figure 21. These components, except for the bistable amplifiers, comprised the components used in the UH-1 fluidic damper system tested under Contract DA 44-177-AMC-294(T). Appendix I describes the life test procedure.

Vortex Rate Sensor

The vortex rate sensor, shown in Figure 21, is a pure fluid device. It has no moving parts and produces a differential output pressure proportional to input turning rate. The sensor pickoff porting was designed so that flow passed through the pickoff ports during the life test; but during the performance tests these passages were closed, with the pickoff port valves shown in Figure 21, so that the output was dead-ended. This was done to ensure that variations in load did not enter into the measured output. Sixteen sensors were fabricated; five were subjected to 50-micron oil, five to 10-micron oil, and five to 10-micron oil with no environmental factors imposed. These units were manifolded in groups as shown in Figure 22.

The sixteenth unit was left on the shelf as a control unit. However, it was eventually necessary to use it in the feasibility system because of problems encountered in that portion of the program. This is described under the paragraph on the feasibility system.

Initially, the units were to be tested with the supply held at a constant pressure. During the second performance test, after 220 hours of running, a number of the sensors did not meet the null and gain requirements,and it was noted that the total flow to each package increased.

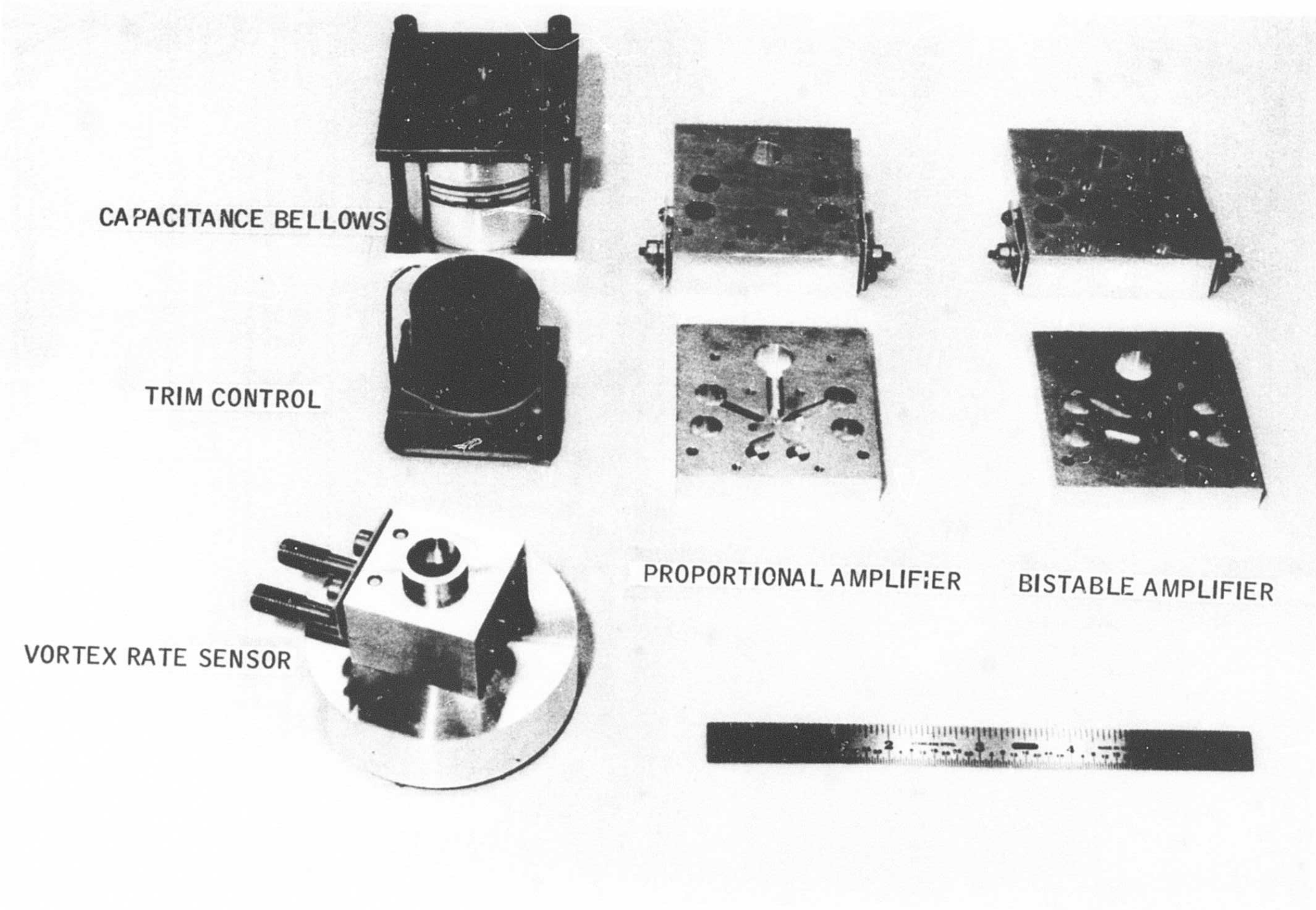


Figure 21. Individual Life Test Components.

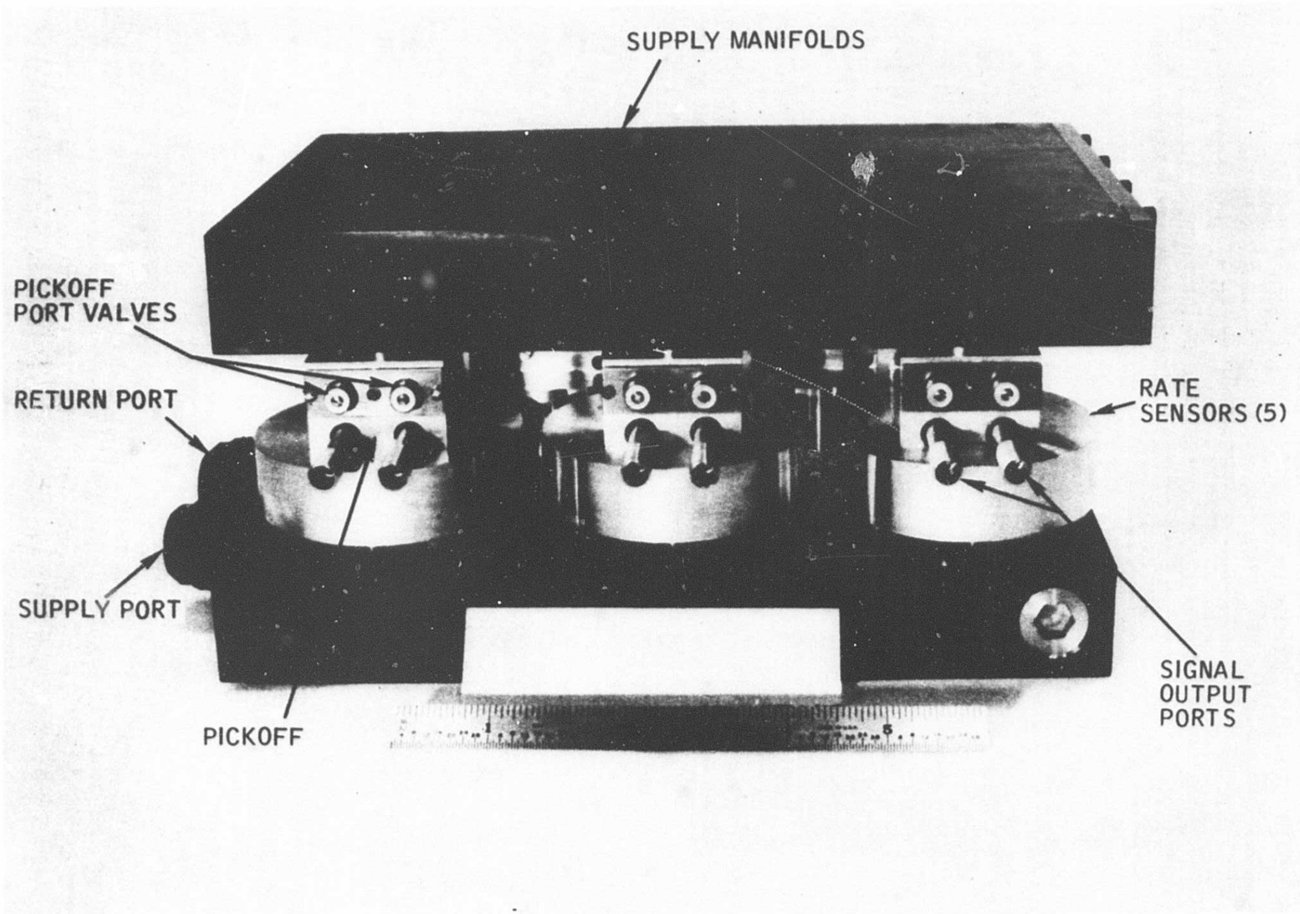


Figure 22. Rate Sensor Test Manifold.

The units were tested individually and performed satisfactorily. By this time two weeks had passed and performance test number two was run. Again, the total flow increased for the same supply pressure. It was then noted that the viscosity of the oil was changing with time. Since the sensor performance is dependent upon mass flow, it was decided to test the units under constant flow conditions to eliminate external effects. All performance tests conducted from this time were run with flow to each sensor package held constant.

At the time of the third performance test, it was noted that the filter was bypassing in both the 50-micron and the 10-micron pumping system. Since the sensors performed satisfactorily, the filters were replaced and testing continued.

At the end of the life test, the units were disassembled and visually examined. Figure 23 shows one of the units from the 10-micron system and Figure 24 shows one from the 50-micron system; the dirty one was run on the 50-micron oil. The major portion of the contamination in the sensors was Styrofoam. It is believed that this entered the system through the reservoir and got into the sensors when the filters were bypassing. Since the majority of the oil passes through the sensors, the contamination would be carried to the sensors more readily than to the amplifiers. Even with this contamination which collected on the coupling element (layers of washers), the performance of the units was satisfactory. Curves of both the 50-micron and 10-micron sensors pictured in Figures 23 and 24 are shown in Figures 25 through 28.

Proportional Amplifier

The proportional amplifier, shown in Figure 21, is a beam deflection type of pure-fluid element. It produces a differential output pressure proportional to a differential input pressure. It is necessary to have flow through both the power port and control ports for proper operation. The interaction region downstream of the power nozzle is vented to the power supply return line. This produces a completely closed unit that can be operated at any supercharge pressure and with output ports dead-ended. Complete load isolation is achieved with this design.

Sixteen units were fabricated. Fifteen units were subjected to the conditions as specified in Appendix I, and one unit was left on the shelf as a control unit. The units were tested in manifolds as shown in Figure 29. Of the 10 in each package, five were proportional amplifiers and five were bistable amplifiers. It was possible to measure the characteristics of the individual amplifiers during each performance test by shutting off, with valves, the output of all amplifiers except the one tested. The units were life tested under dead-ended load conditions, simulating a power amplifier driving an actuator.

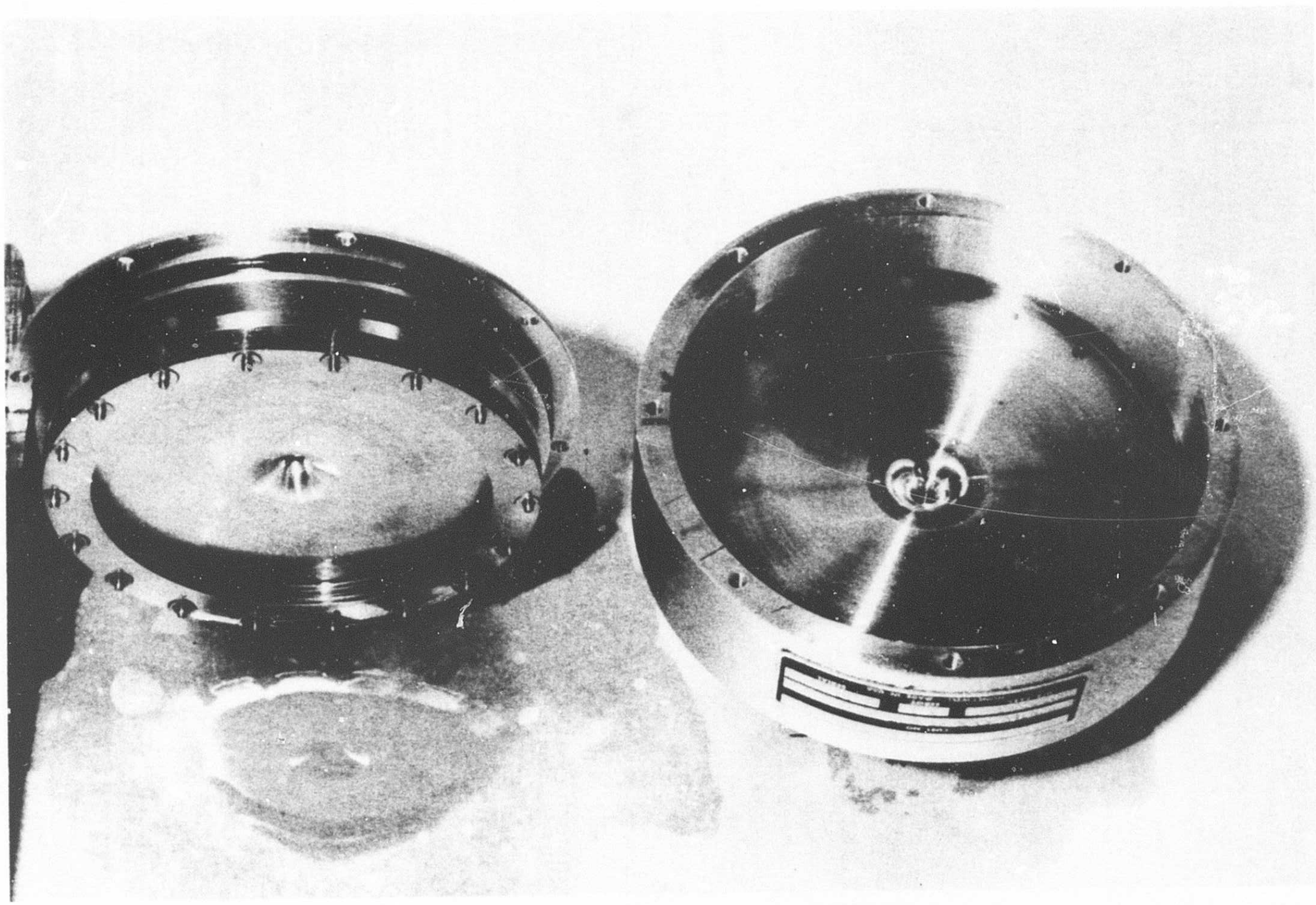


Figure 23. Rate Sensor Run on 10-Micron Oil System.

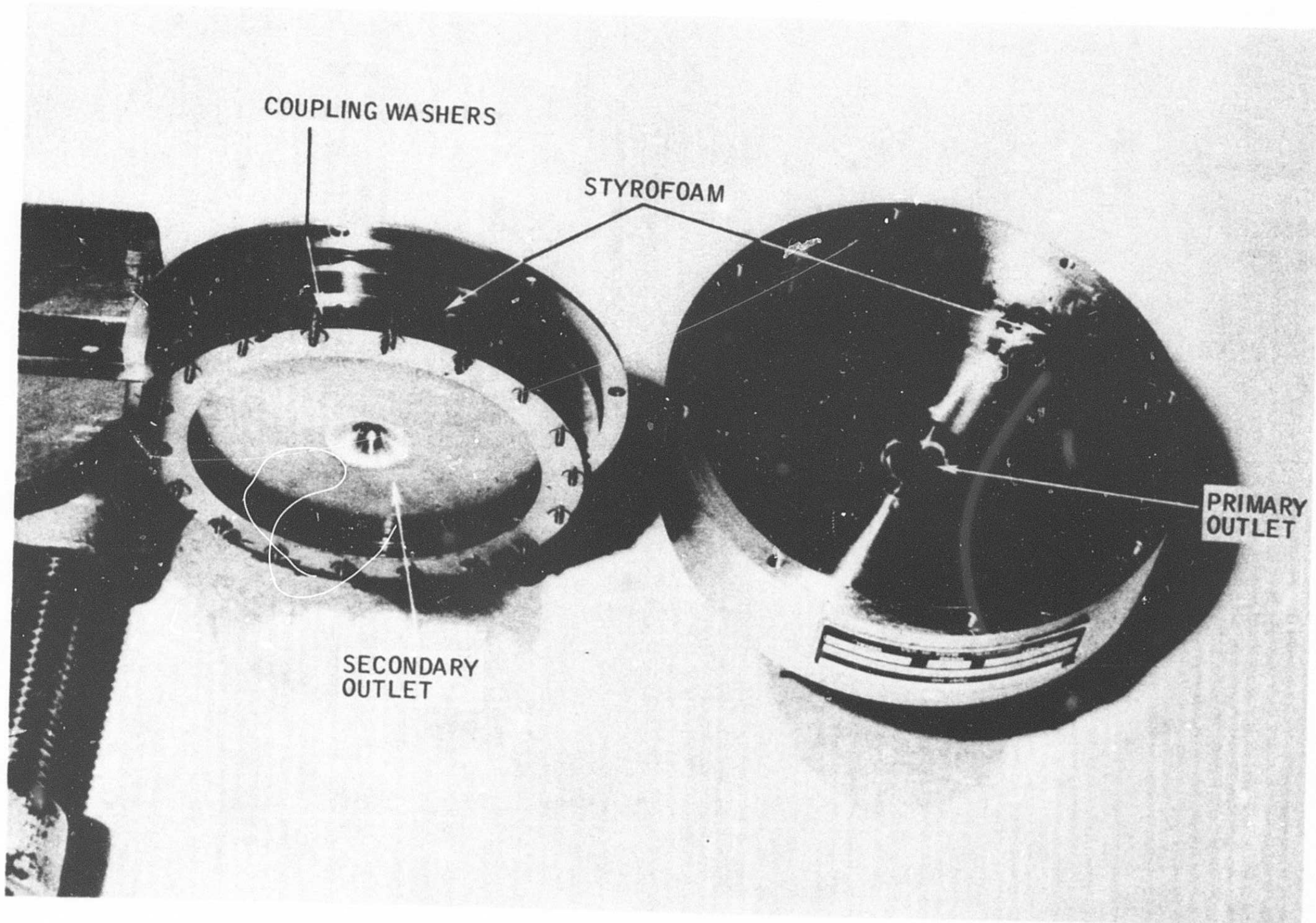
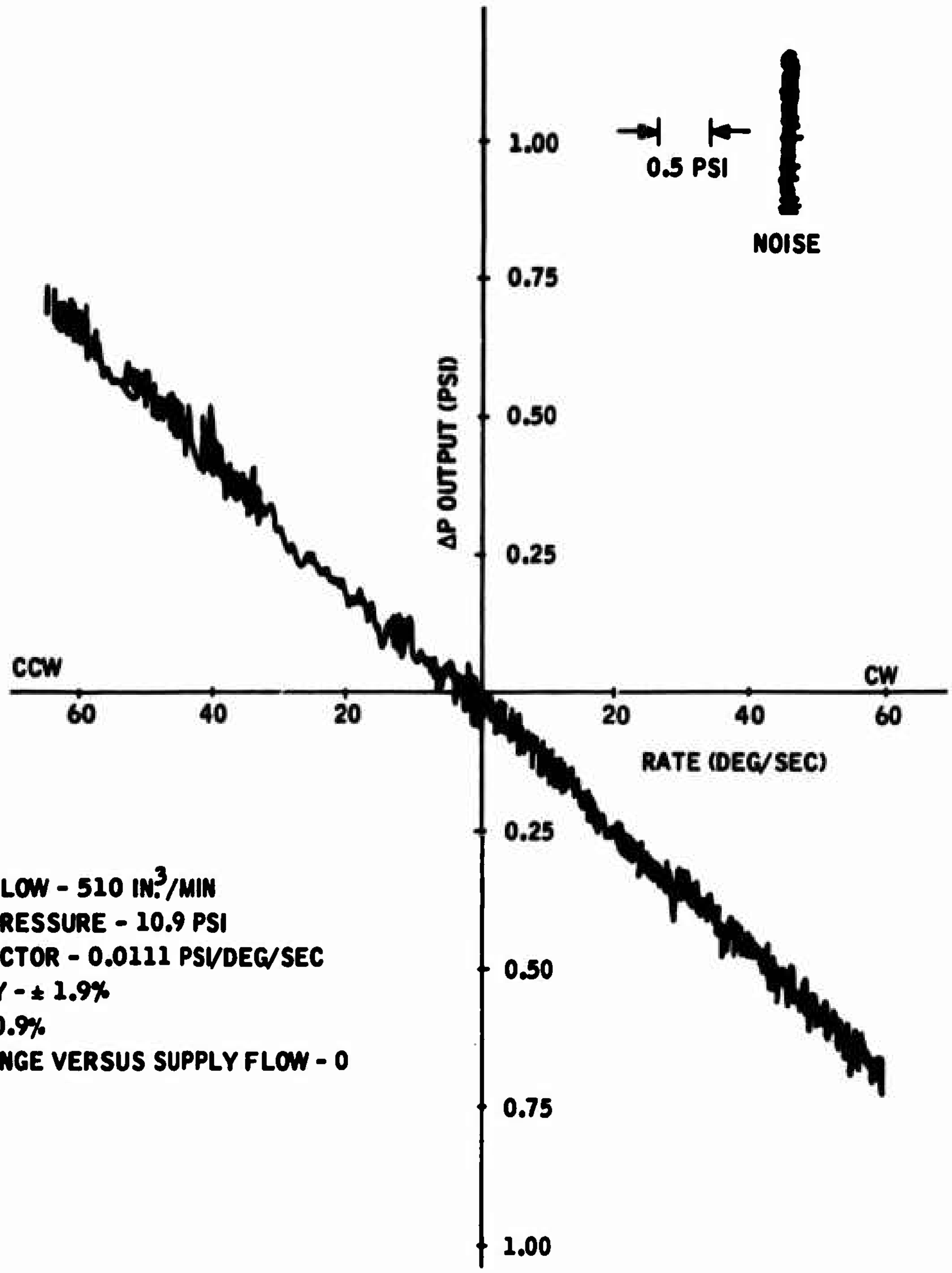


Figure 24. Rate Sensor Run on 50-Micron Oil System.



S/N 4
SUPPLY FLOW - 510 IN.^{3}/MIN
SUPPLY PRESSURE - 10.9 PSI
SCALE FACTOR - 0.0111 PSI/DEG/SEC
LINEARITY - ± 1.9%
NULL - -0.9%
NULL CHANGE VERSUS SUPPLY FLOW - 0

Figure 25. Initial Performance Curve, Rate Sensor, 50-Micron Oil System.

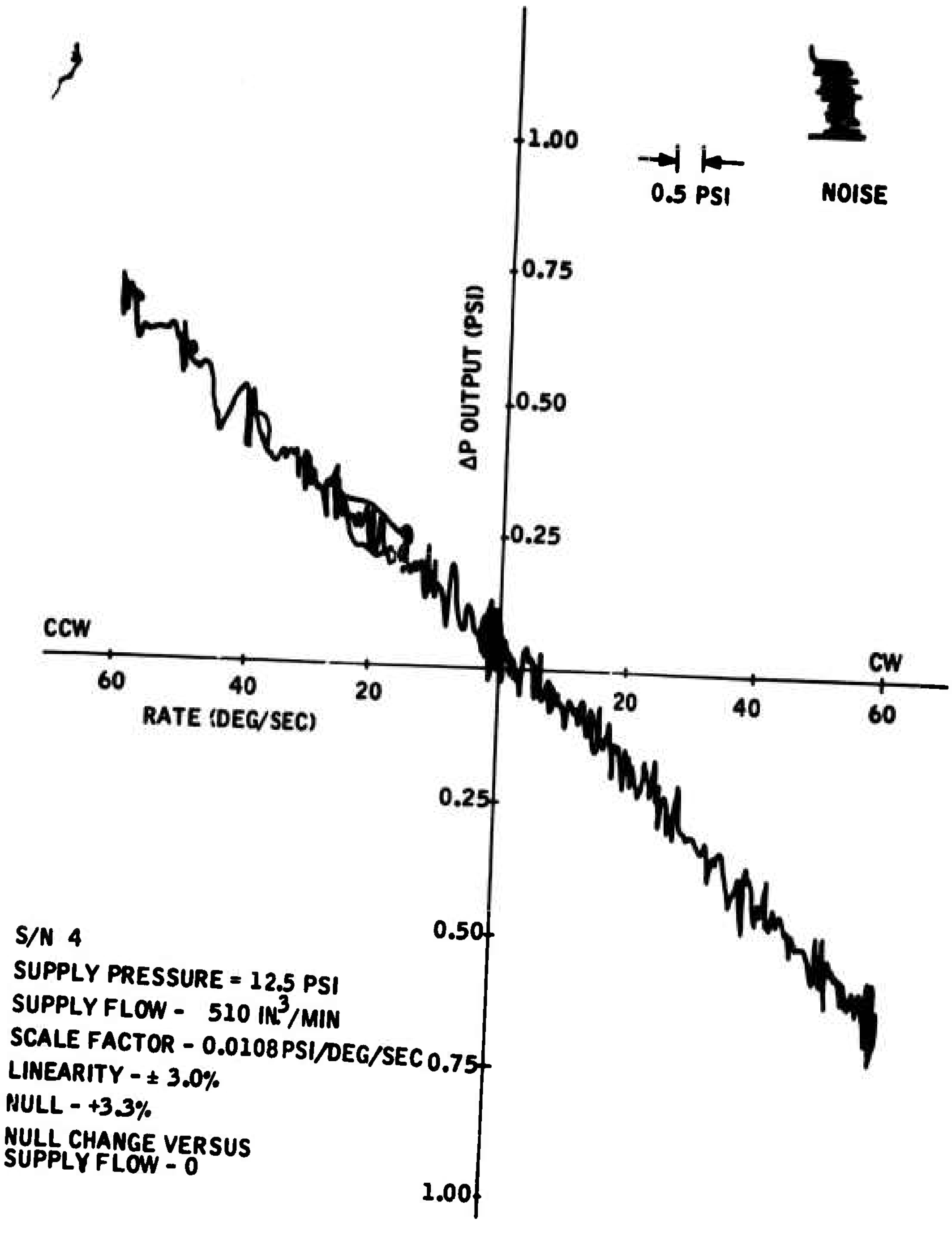


Figure 26. Final Performance Curve, Rate Sensor, 50-Micron Oil System.

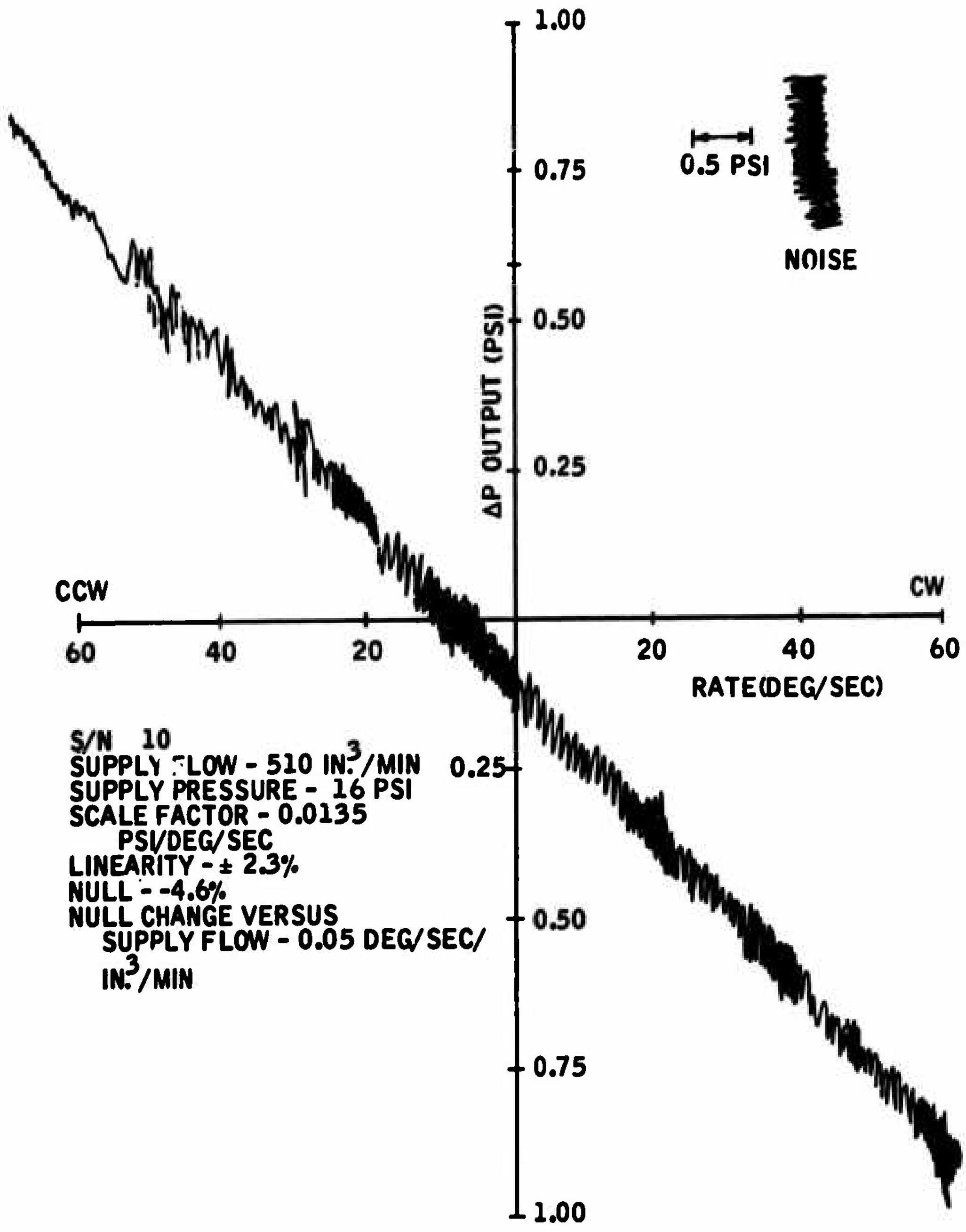


Figure 27. Initial Performance Curve, Rate Sensor, 10-Micron Nonenvironmental Oil System.

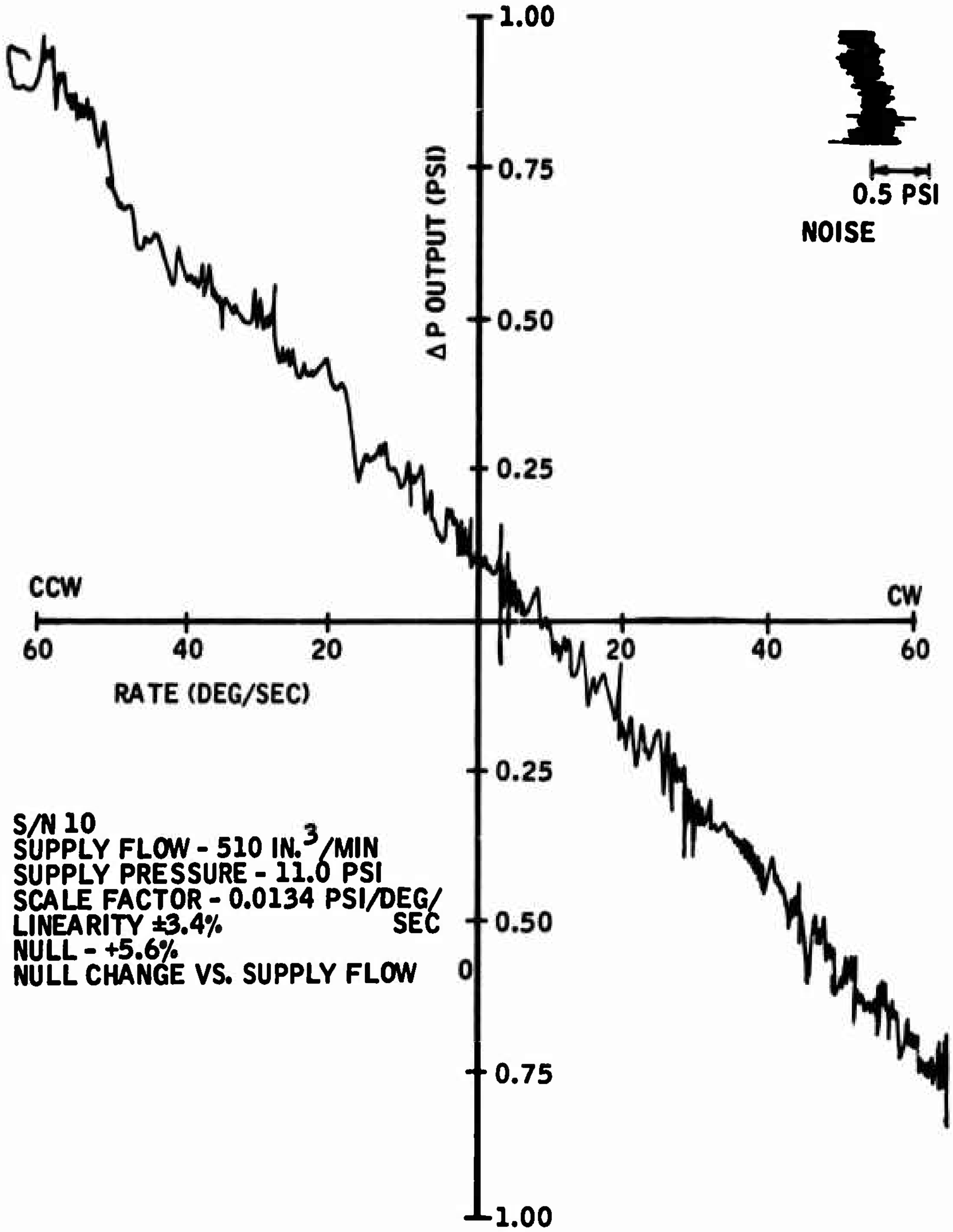


Figure 28. Final Performance Curve, Rate Sensor, 10-Micron Nonenvironmental Oil System.

As in the case of the rate sensors, the pressure drop through the amplifiers originally was to be held constant at 10 psi. At the second performance test, a number of units were outside the linearity second failure limit. These units were removed and tested individually; all performed satisfactorily. It was decided to run the units manifolded together during the life test , as shown in Figure 29; however, during performance testing,they would be tested individually. This would remove the influence of the other units, both bistable and proportional, on the unit being tested and allow the units to be tested under constant flow instead of constant pressure. After this change, the units performed satisfactorily for the remainder of the test.

Figure 30 shows one of the amplifiers from the 10-micron oil system. No wear or contamination was found in any of the units when they were disassembled. Performance data for this particular amplifier are shown in Figures 31 and 32.

Capacitor Bellows

The capacitor bellows (Figure 21) is a moving-part device. It is used to provide capacitance for the hi-pass network of the UH-1B system (see Figure 43) in conjunction with two amplifiers. The capacitance level is controlled by the spring rate of the bellows. One side of the bellows is normally subjected to the system signal,and the other side is referenced to the return line pressure. To measure spring rate of the bellows, only one side was pressurized during the life test. This allowed a probe to measure the bellows deflection for changes in input pressure. The life test fixturing is shown in Figure 33.

Between the first performance test and the second performance test, it was noted that the bellows on the 50-micron system had been overpressured and were damaged beyond repair. The exact cause of this overpressure is not known. The bellows were replaced with new units and testing continued. To determine the pressure necessary to damage the bellows, a new bellows was intentionally overpressured. At 55 psig the bellows collapsed. To supply the flows to all life test components, the supply pressure was 90 psig. The pressure was reduced through a valve to place approximately 2 psig on the bellows. A valve was located downstream of the bellows for use during the performance tests. It is possible that this valve became clogged momentarily, causing the pressure on the bellows to exceed 55 psig. As the pressure on the downstream valve increased toward 90 psig, it is possible that this high pressure forced the contamination through the valve, returning the pressure on the bellows to normal. To prevent a reoccurrence of the overpressure, relief valves were installed just upstream of the bellows. The valves were set at 10 psig, well below the failure point of the bellows. No failures occurred during the rest of the life test.

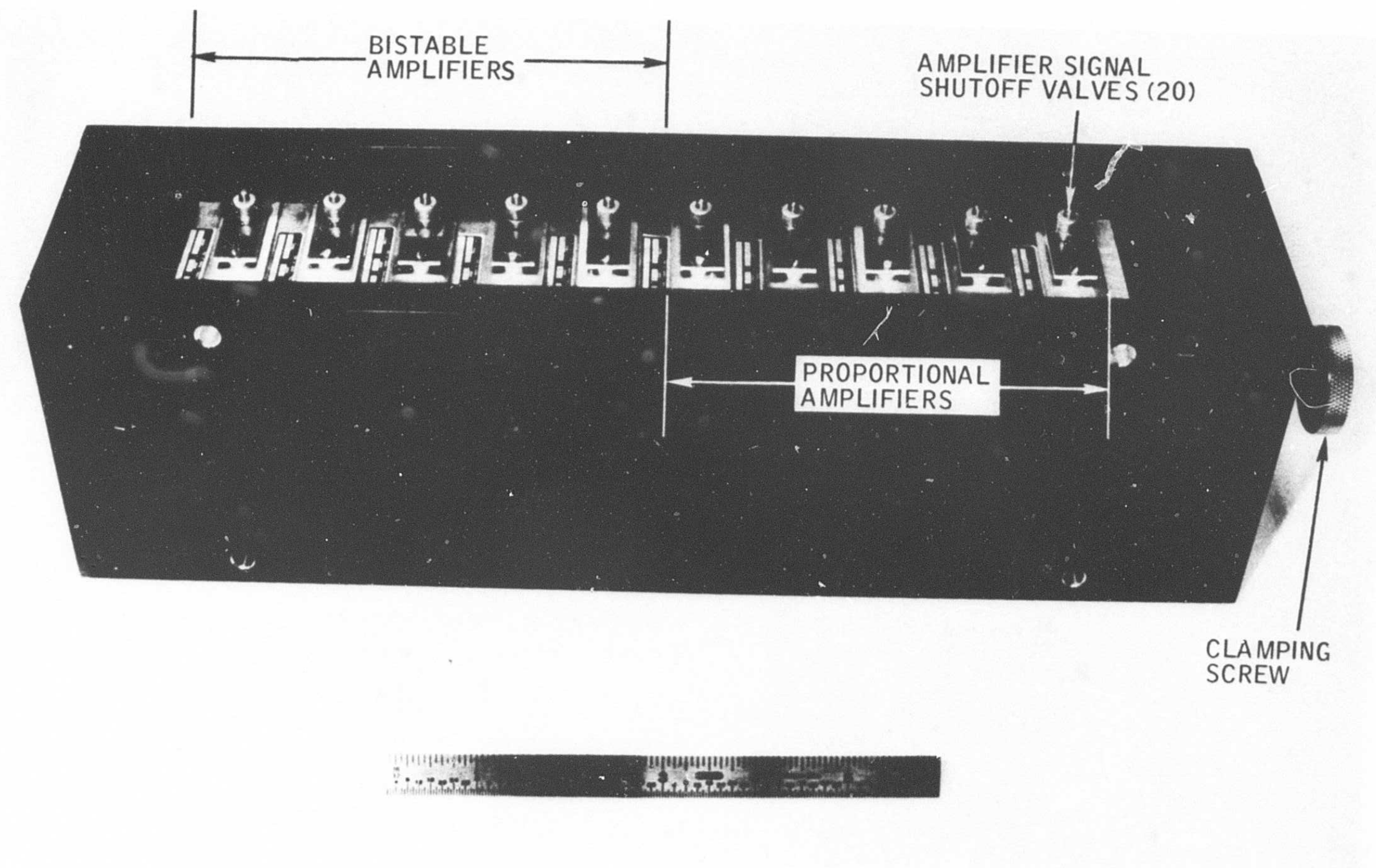


Figure 29. Amplifier Test Manifold.

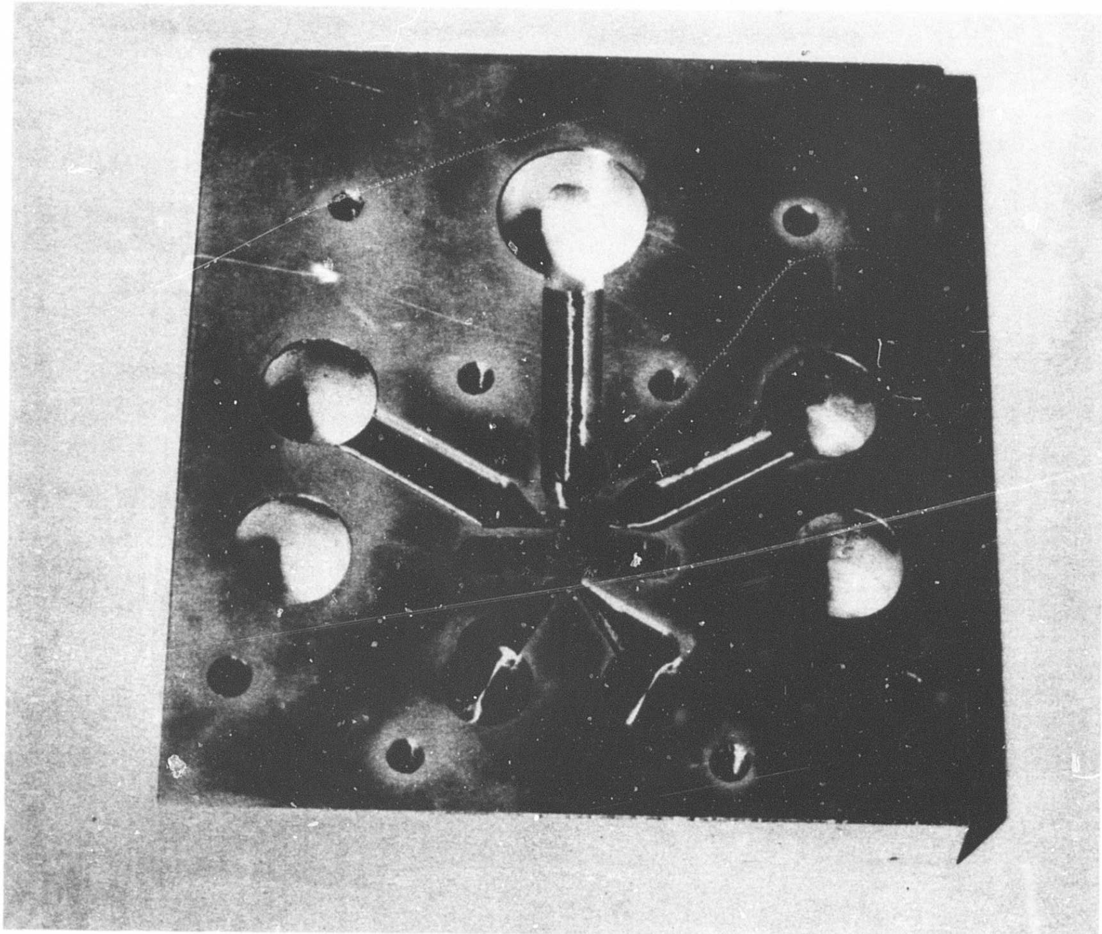


Figure 30. Prop Amplifier Run on 10-Micron Oil System.

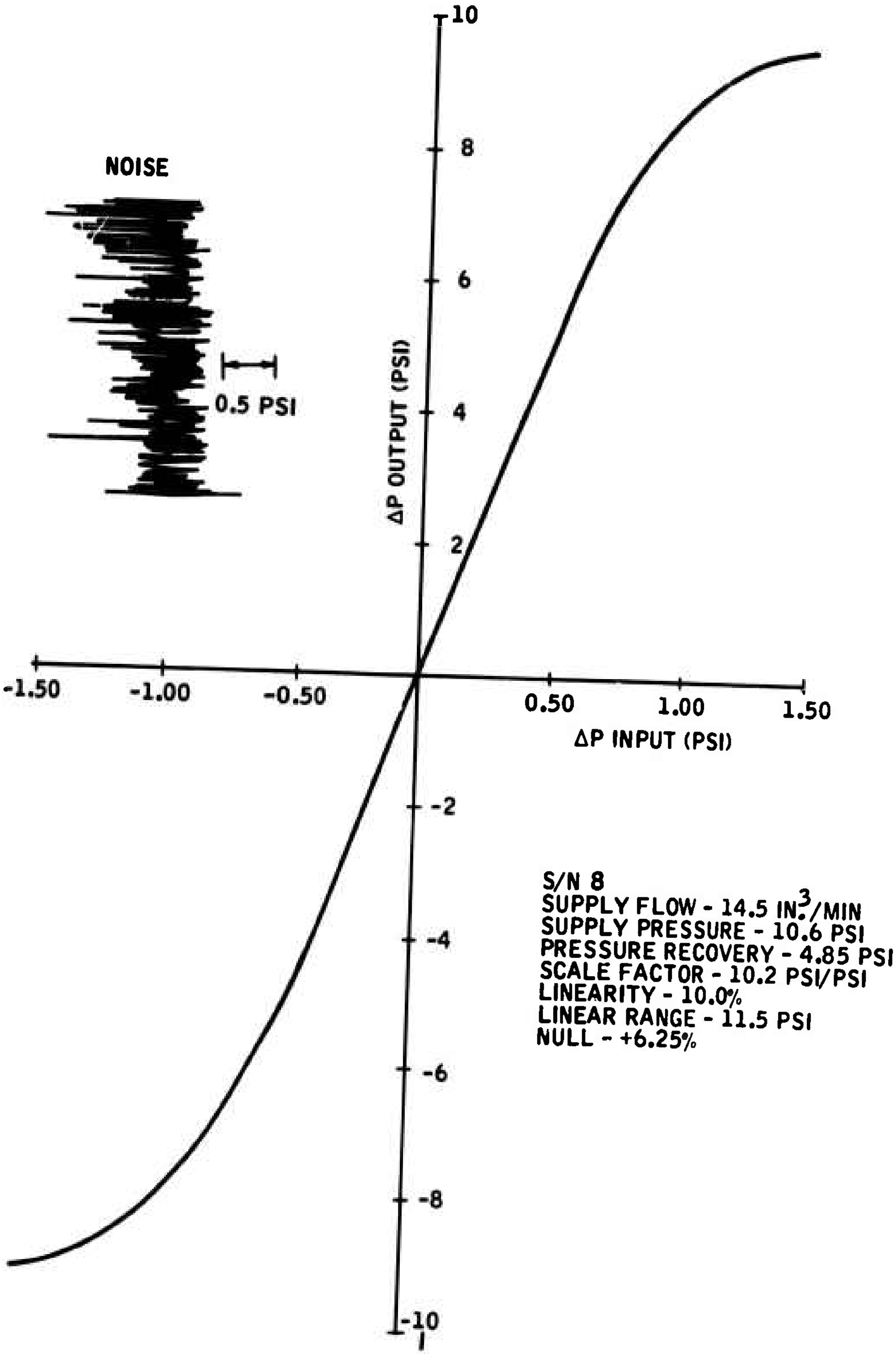


Figure 31. Initial Performance Curve, Proportional Amplifier, 10-Micron Oil System.

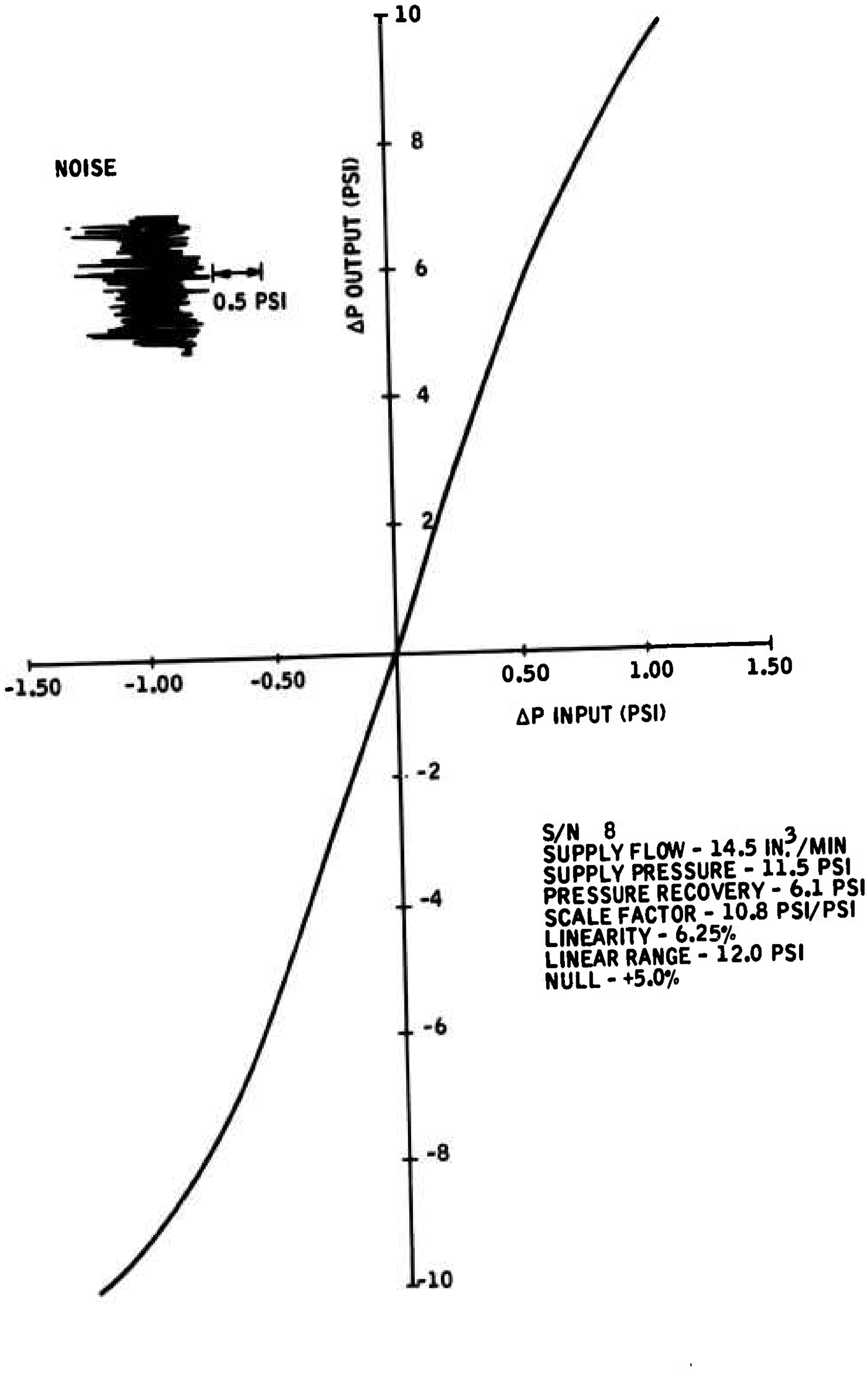


Figure 32. Final Performance Curve, Proportional Amplifier, 10-Micron Oil System.

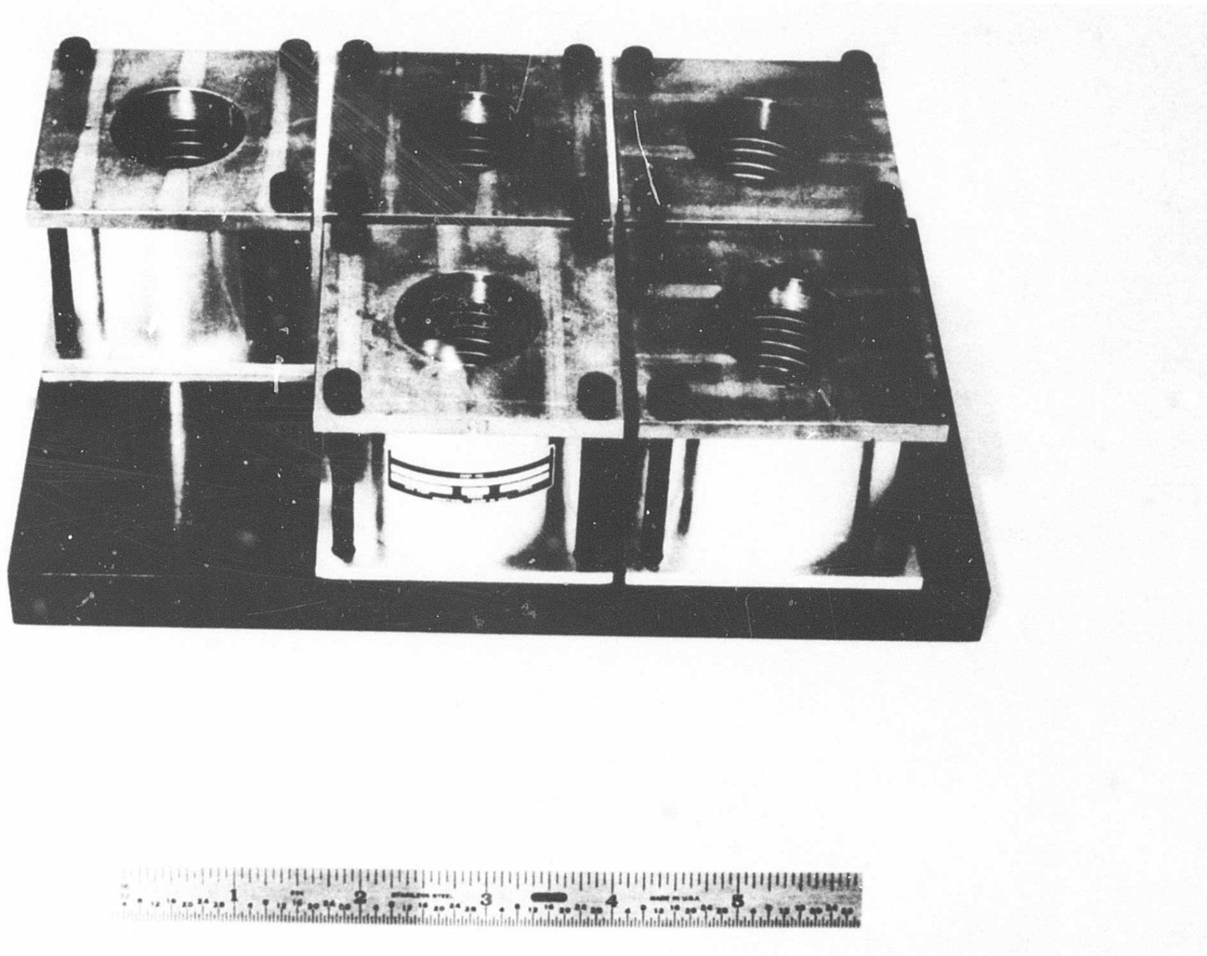


Figure 33. Bellows Life Test Manifolding.

The initial and final performance curves of a typical bellows are shown in Figures 34 and 35.

Trim Control

The trim controls, shown in Figure 20, were purchased items from Cadillac Gage Company. They produce a differential output pressure proportional to input voltage. These units were mounted in groups of five (Figure 36) and were subjected to the conditions and tests as specified in Appendix I.

Almost immediately after the start of the life test, the units subjected to the 50-micron oil ceased to operate. After checking with Cadillac Gage, it was found that the units had an internal 10-micron filter. The five units from the 50-micron oil system were removed and sent to Cadillac Gage to have the 10-micron filters replaced with 60-micron filters. All units performed satisfactorily afterwards. Some indication that contamination was occurring was observed, usually a flattening of the ends of the gain curve. However, this would go away after vibration.

The initial and final performance curves of a typical trim control are shown in Figures 37 and 38.

Bistable Amplifier

The bistable amplifier shown in Figures 21 and 39 does not use the Coanda or wall-attachment effect. The bistable action is achieved by having a cusp on the splitter so that flow is returned in a positive feedback type operation, forcing the power stream hard over against the amplifier wall. The input signal moves the power stream part way from one output port to the other, and then the feedback from the cusp completes the switch. Since it is necessary to have a high Reynolds number to achieve wall attachment, a very large amplifier (large flow) or a very high supply pressure would be required. Therefore, it is not practical to make a bistable amplifier using the wall-attachment effect.

For the life test,the bistable amplifiers were manifolded together with the proportional amplifiers as shown in Figure 29. They were also tested in the same manner; valves on the output ports were operated to allow the testing of each individual unit. After the second performance test, the procedure of testing the bistable amplifiers was changed (as with the proportional amplifiers) from testing the units manifolded together to testing them individually. Also, the power

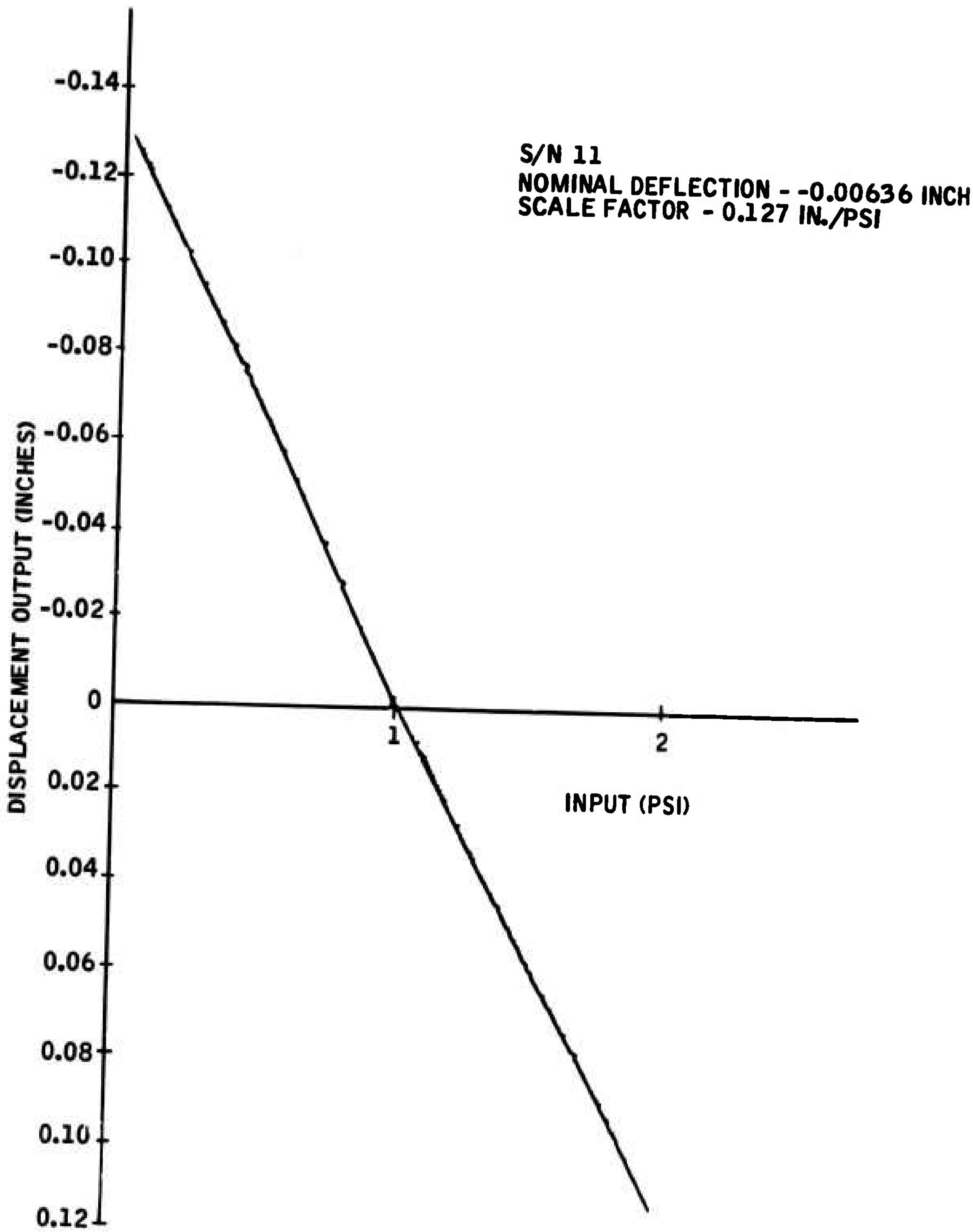


Figure 34. Initial Performance Curve, Bellows, 10-Micron Oil System.

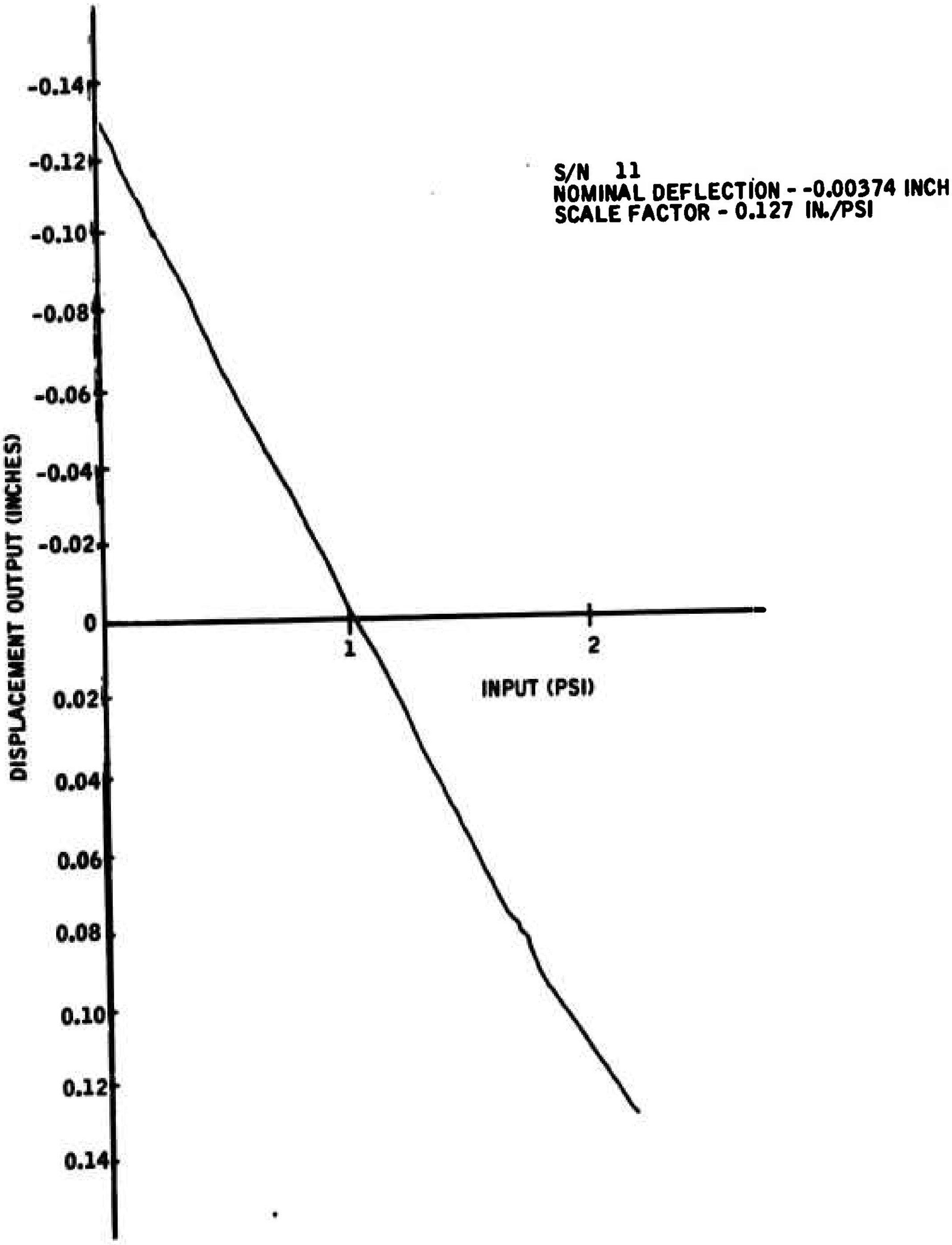


Figure 35. Final Performance Curve, Bellows, 10-Micron Oil System.

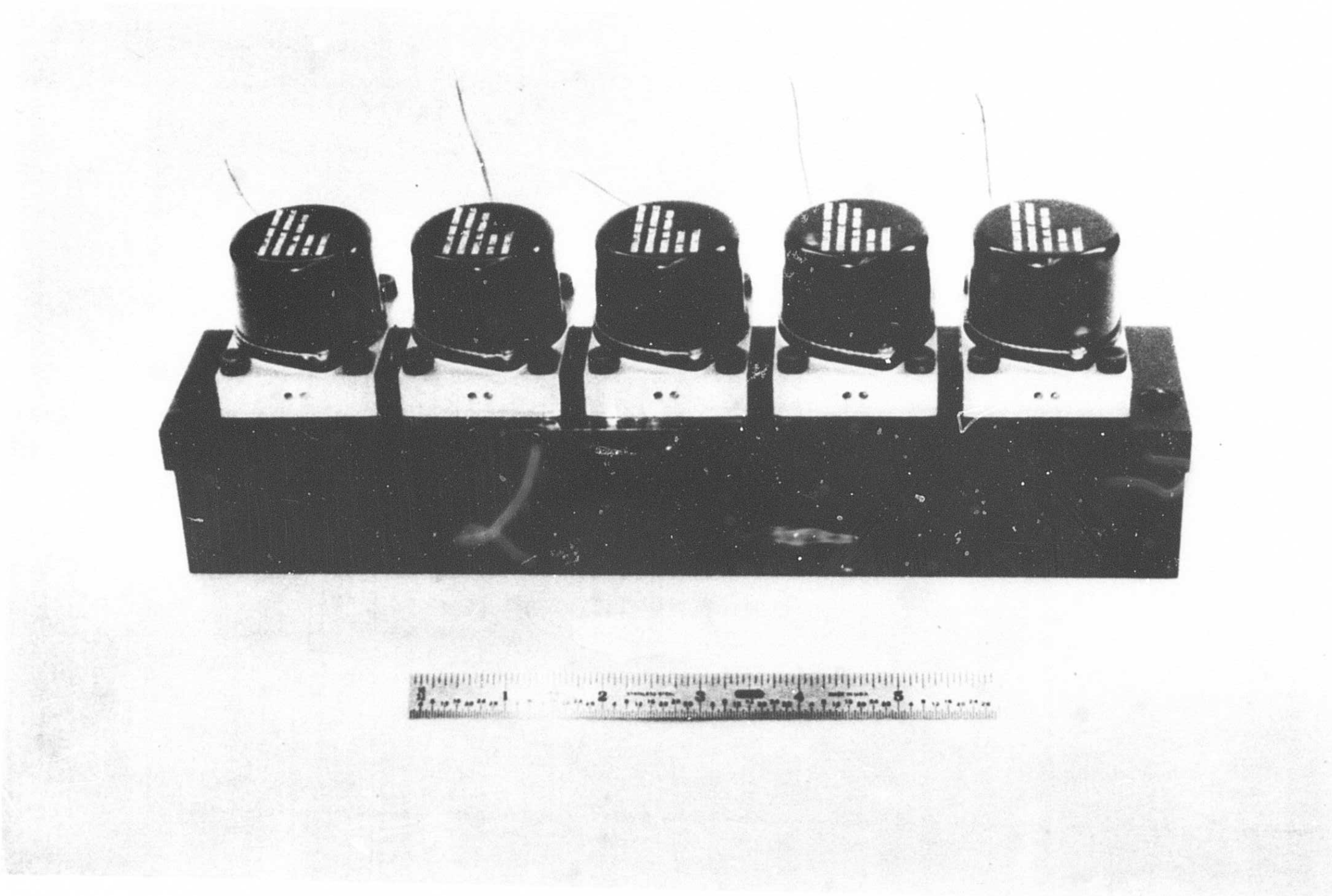


Figure 36. Trim Control Life Test Manifolding.

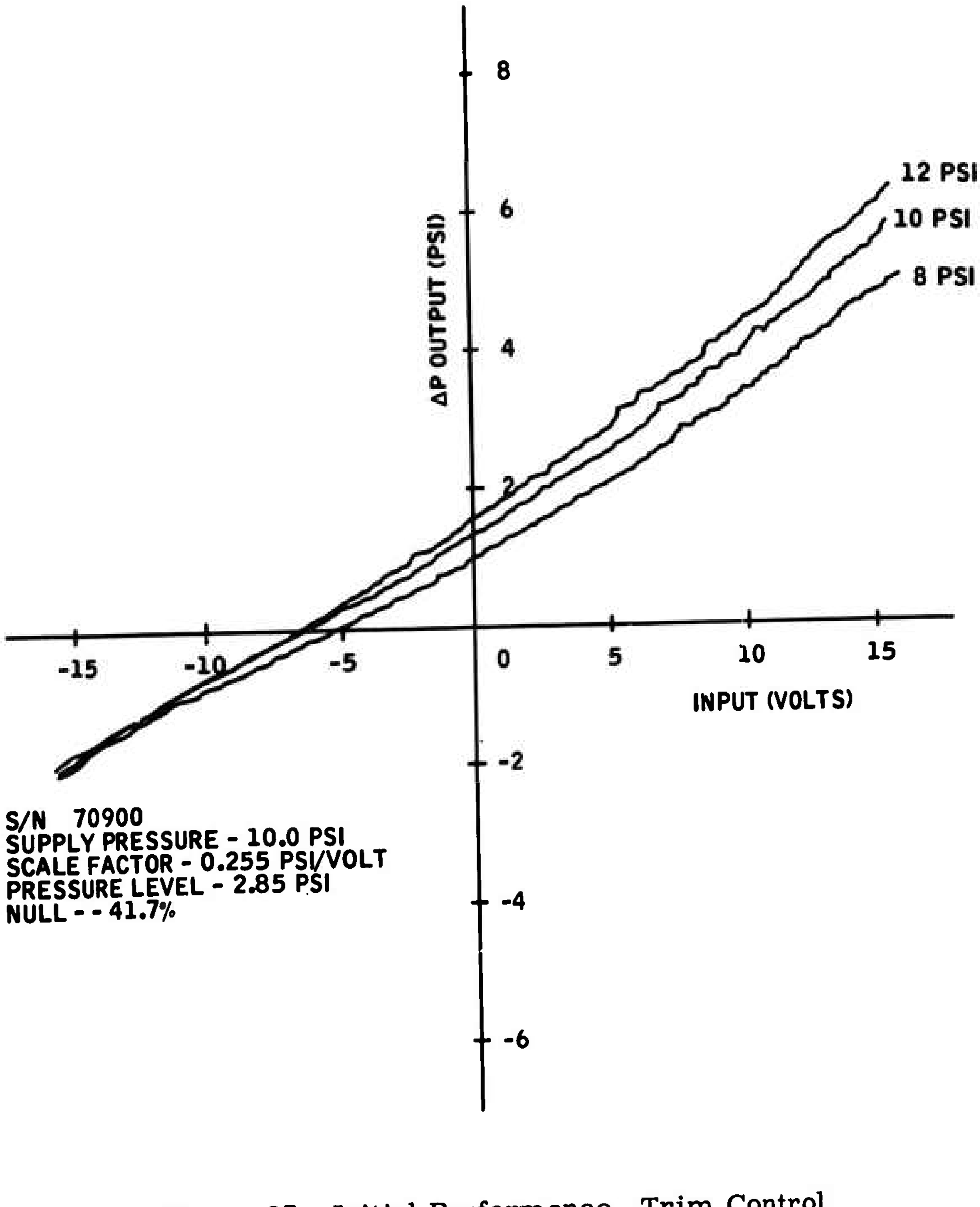


Figure 37. Initial Performance, Trim Control Valve, 10-Micron Oil System.

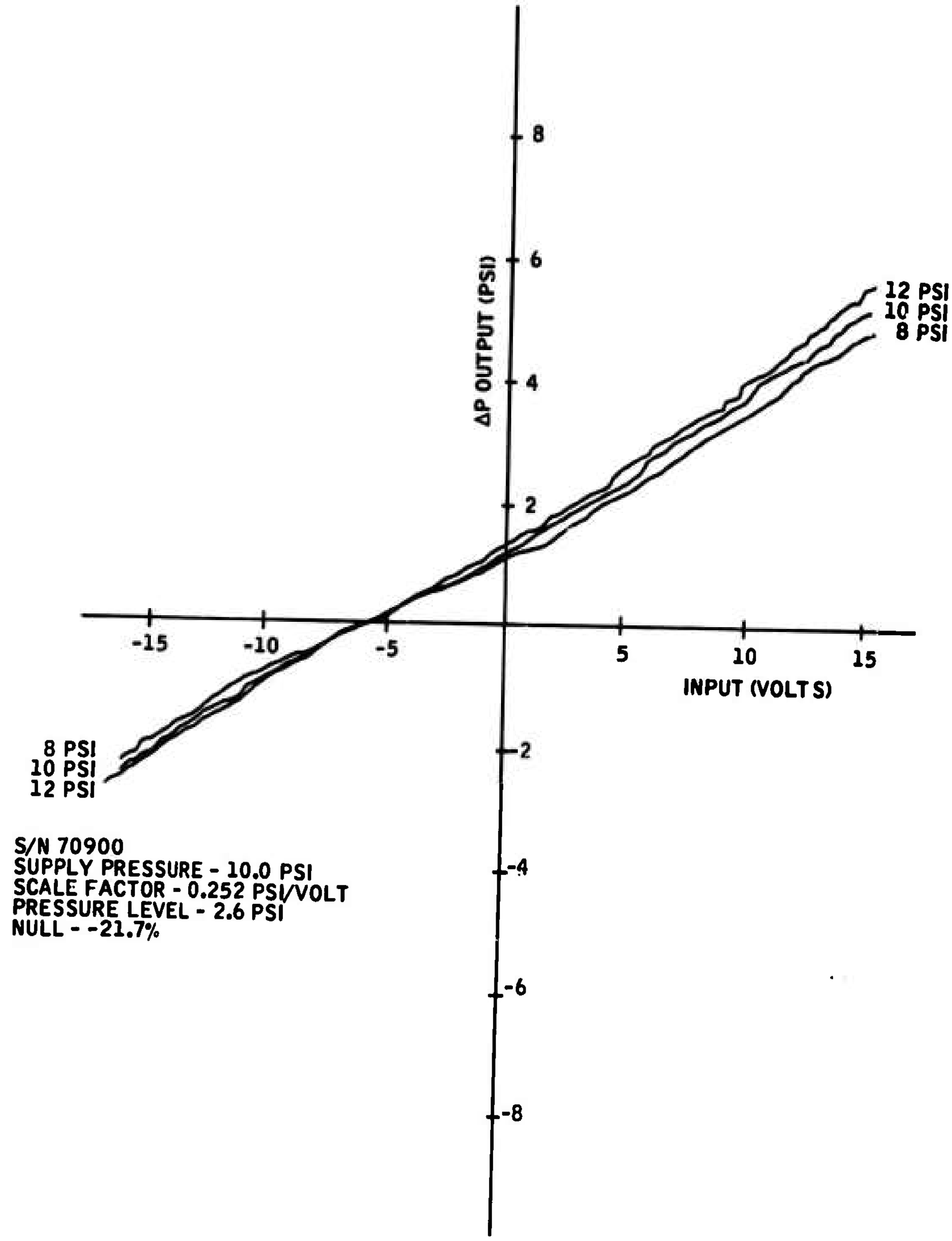


Figure 38. Final Performance, Trim Control Valve, 10-Micron Oil System.

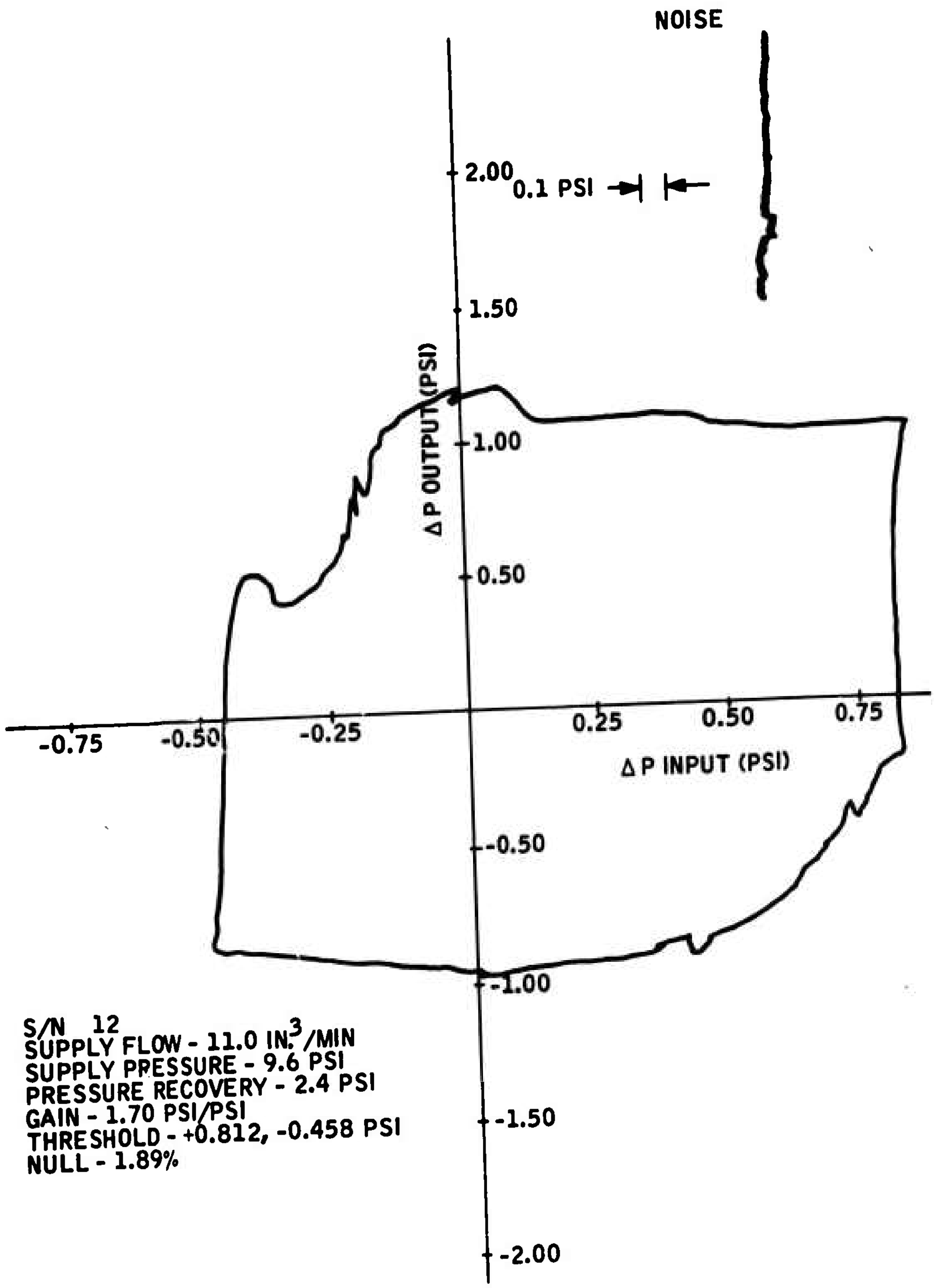


Figure 39. Initial Performance, Bistable Amplifier, 50-Micron Oil System.

supply conditions were changed from constant pressure to constant flow. This was done because it was thought that the erratic performance of the units was caused by the interaction of one unit with the other and the inability to measure the flow to the individual units during the performance tests. Changing the test procedure did not change the variation in performance tests. The instrumentation was checked, tests were run at constant pressure instead of constant flow, and an accumulator was added to the supply line to minimize noise, but no improvement in repeatability was obtained. It is possible that noise caused the variation in switching levels, even with the accumulator on the power supply line. When the input signal nears the point where the unit will switch, a small noise variation could cause the unit to switch. This can be seen in Figures 39 and 40, which are the initial and final performance curves of the amplifier shown in Figure 41. A slight change in the input noise level could have caused premature switching, indicating a gain (ΔPout/ΔPin) change. If the switch point changes only on one side, a null shift would also be indicated.

One of the units was removed, disassembled, and examined under a microscope after running for 965 hours. A small amount of silting was noted in the power port and input ports. This could be removed easily with a wooden stick. The unit was cleaned and placed back in the life test. The performance was not affected by the removal of the silt. Examination of the units at the end of the life test revealed no contamination in the power or input ports. A unit from the 50-micron oil system is shown in Figure 41. It is assumed that this unit also had silt in the ports, as in the above amplifier, but continued operation washed it away.

Because of the test procedure change from constant pressure to constant flow conditions, the failure limits were based on the performance obtained after the units had undergone testing for approximately 350 hours. The initial test data shown in Figure 39 were taken at this point.

HYDRAULIC YAW DAMPER SYSTEM

Description of Hydraulic Yaw Damper

The hydraulic yaw damper system developed to show feasibility of a fluidic damper for the UH-1 helicopter is shown in Figure 42. This system was developed and feasibility proved under Contract DA 44-177-AMC-294(T). The mechanization diagram of the yaw damper is shown in Figure 43. It consists of a hydraulic rate sensor with the fluid output amplified, hi-passed, and then fed directly to the series augmentation servo. A "trim" is provided to bias-out any system null offset. The use of hi-pass yaw rate effectively eliminated damper opposition to yaw commands by the pilot, and the use of a series servo eliminates feedback of the damper commands into the rudder pedals. The hi-pass also minimizes the effects of any rate sensor drift.

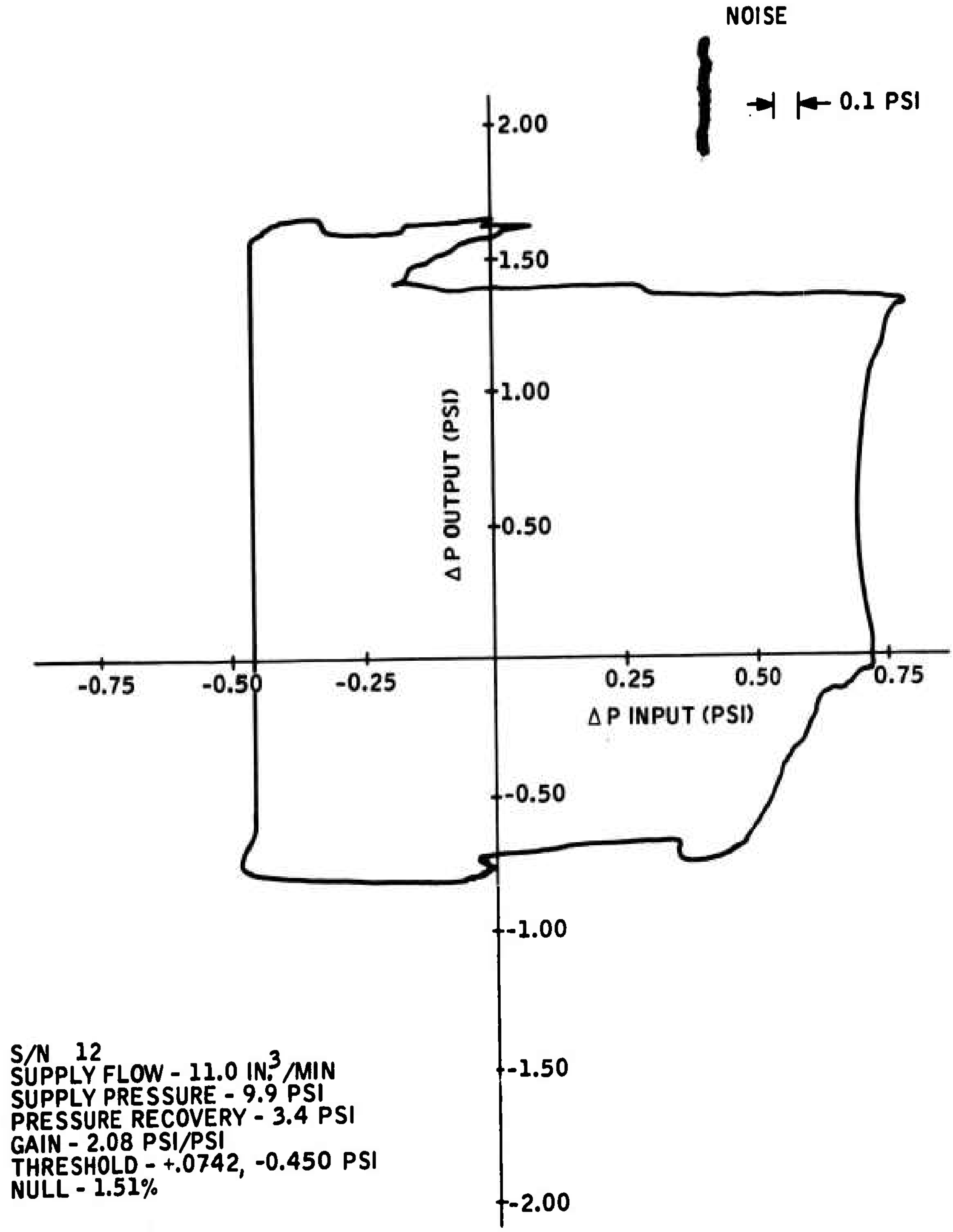


Figure 40. Final Performance, Bistable Amplifier, 50-Micron Oil System.

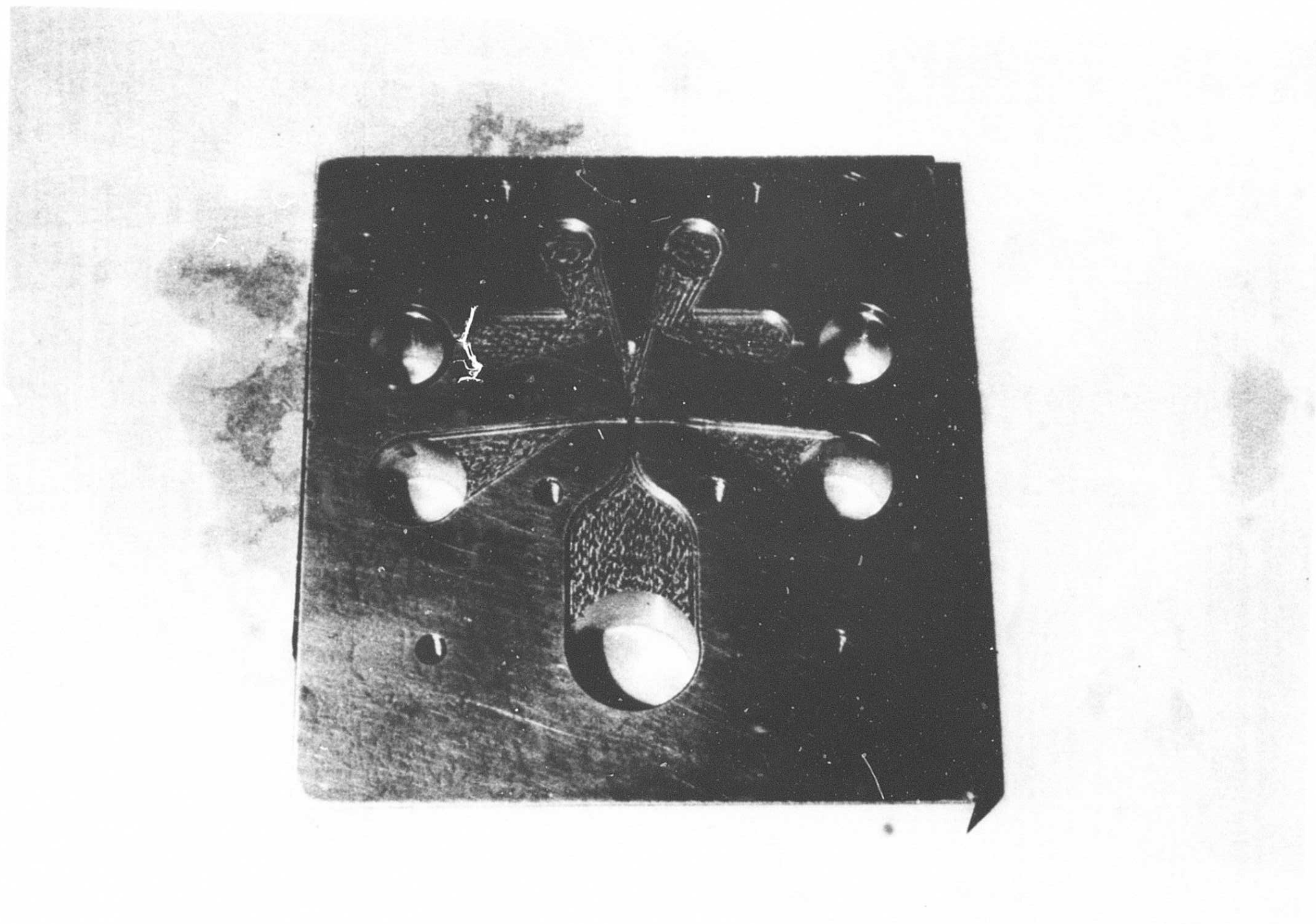


Figure 41. Bistable Amplifier Run on 50-Micron Oil System.

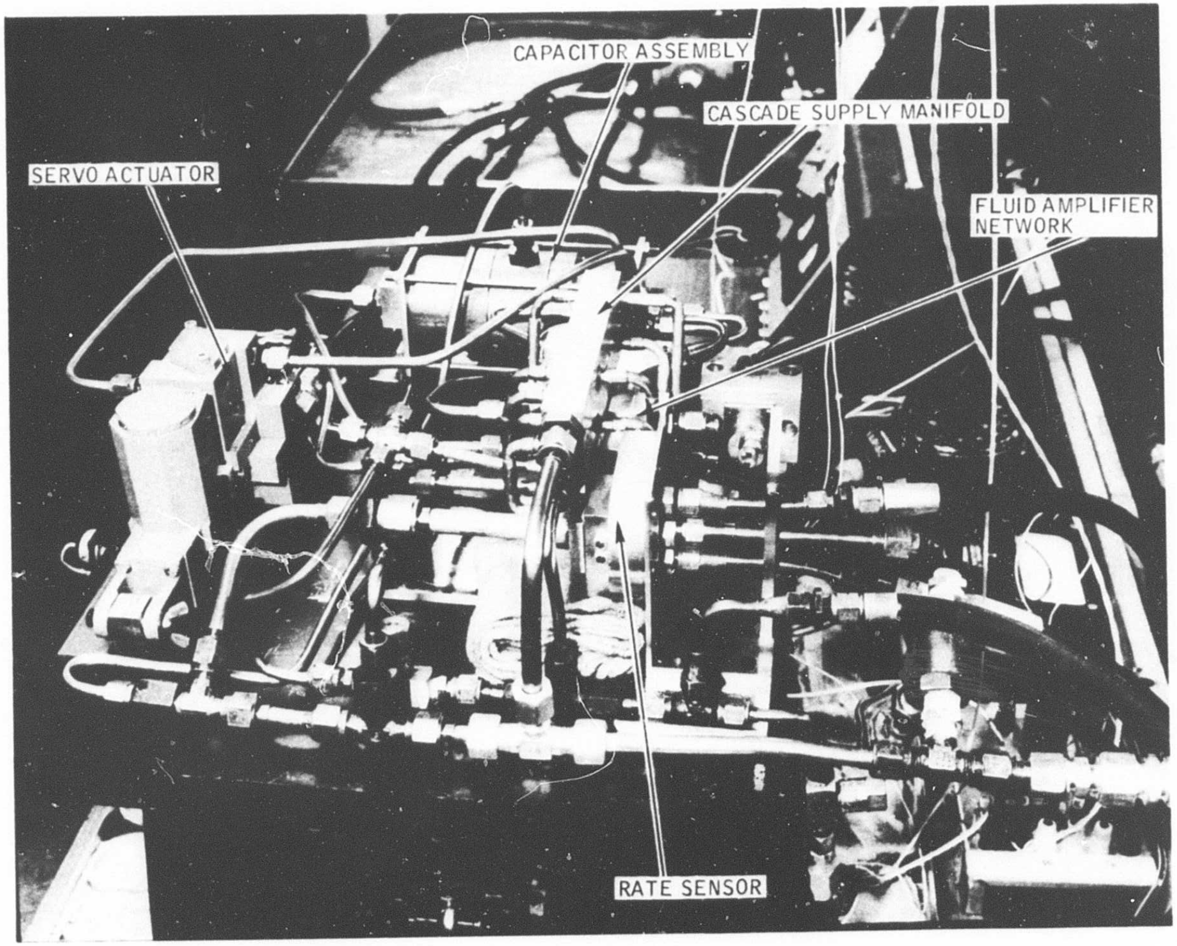


Figure 42. Feasibility Damper System.

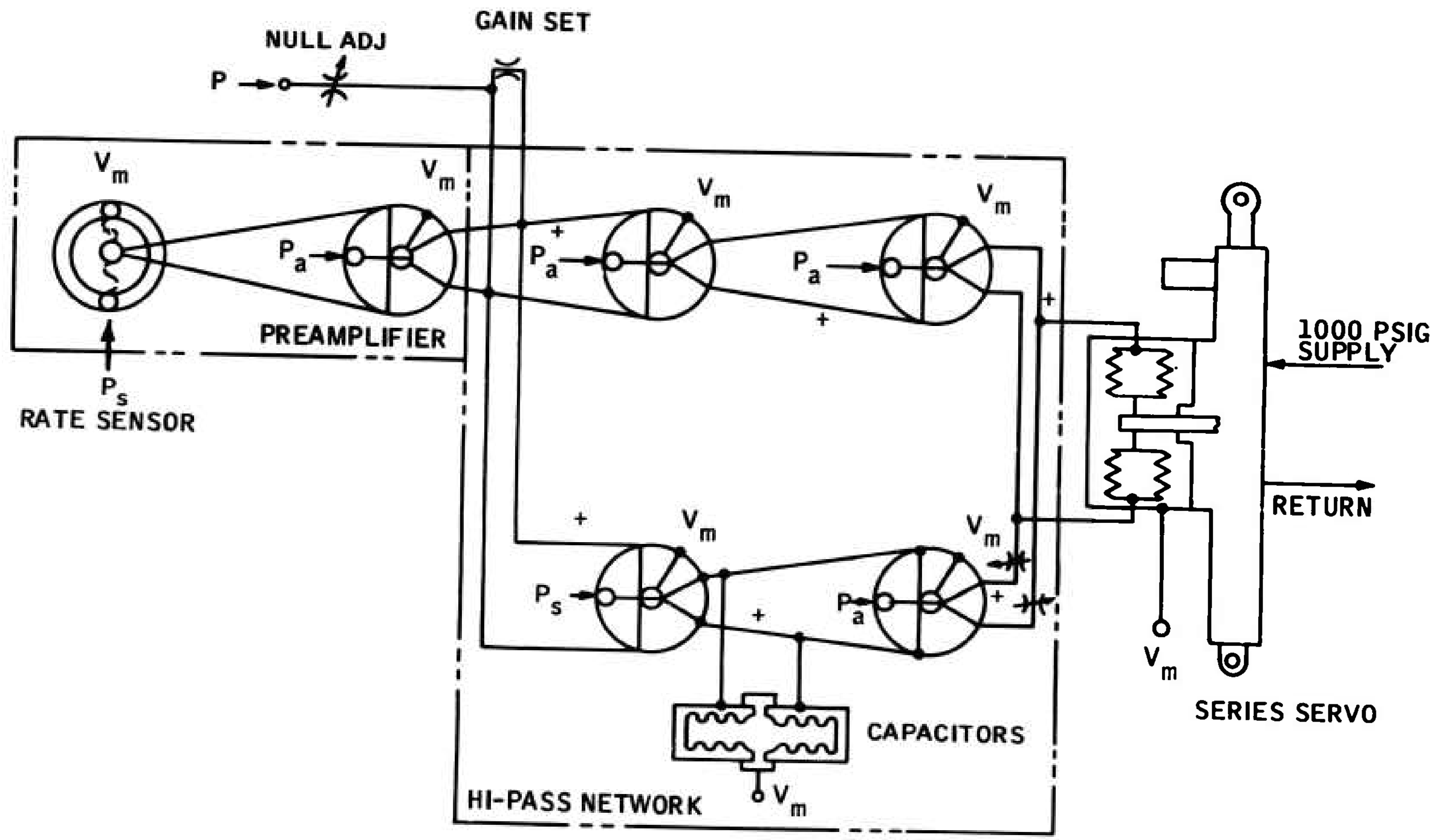


Figure 43. Yaw Damper Fluidic Mechanization Schematic.

The shaping network, hi-pass, consists of a straight-through amplifier cascade with a lagged amplifier cascade parallel in-phase connected at the input and parallel out-of-phase connected at the output. Both cascades have the same gain. The lagged cascade is a low-pass filter with the RC time constant produced by the hydraulic resistances of the input amplifier receiver ports and the output amplifier control ports in conjunction with parallel connected hydraulic capacitors (metallic bellows).

The shaping network cancels the effect of d-c input signals by subtraction at the output, but it permits the passage of a-c input signals by attenuating these signals in the low-pass filter section.

Reworks

Some difficulity was encountered in preparing the system for the flight simulation tests. Because of the time lapse between the end of testing under Contract DA 44-177-AMC-294(T) and the beginning of this contract, the complete system was disassembled and thoroughly cleaned. The system was replumbed to reduce signal-line lengths, to add valves in the hi-pass circuit output to facilitate testing in the shorted hi-pass mode without disconnecting lines, and to add an electrical trim control. Also, the sensor pickoff was redesigned to include the latest null adjustment capability.

A problem encountered at this time was that the system gain was very low; sufficient flow was not getting to the rate sensor. After the rate sensor plumbing was changed so that its supply and return lines were separate from the cascade lines, the gain increased to an acceptable level. Provision was made at this time to allow the sensor and cascade to be tested separately. The system performed as well as, or better than, the earlier configuration during the closed-loop tests.

The system was then mounted, with the input axis vertical, on the rate table for steady-state tests. The gain of the system increased by over a third (0. 033 to 0. 045 in. actuator/deg/sec) of that obtained with the input axis horizontal. This gain change could be repeated each time simply by changing the orientation of the system input axis from horiontal to vertical. The problem was traced to the rate sensor. It possibly was a leak problem in the high-impedance pickoff area caused by mechanical stress each time the input axis was horizontal, but the exact cause was not determined because the life test had to be started. The rate sensor was replaced with the life test unit which was to be used as the control unit.

With the new sensor, the noise measured at the actuator increased to a level above the limit set by the failure criteria. The feasibility pickoff from the feasibility model was installed in the life test sensor housing, but the noise did not decrease. The life test pickoff was reinstalled, and the rate sensor output noise was measured with flow only through the pickoff outlet and secondary outlet. With flow through the secondary outlet only, the pickoff still had a noisy output. It was considerably noisier than with flow passing through the pickoff outlet. This indicated that the manifolding for the rate sensor was a large cause of the noise. The manifolding was reworked to reduce changes in porting size. This reduced the noise level at the actuator approximately 35 percent, from ±0.04 to ±0.025 in./deg/sec.

The next step was to work with the pickoff of the rate sensor. Various techniques were tried (thinner blades and stiffer hold-down springs), but the final solution was clamping the pickoff blade solidly into the housing. This reduced the noise level at the actuator to ±0.014 in./deg/sec.

Also, at this time the electrical trim control was replaced by a mechanical needle valve, and a shunt was placed across the output of the preamp. The electrical trim control was distorting the output of the preamp, because it is a pressure-balanced valve looking into an impedance that is not infinite. The shunt was needed to obtain the desired gain level. The shunt was originally placed at the rate sensor output, but, because of the low differential pressure between the two output lines of the rate sensor, it was not possible to obtain suitable low impedance (short-out enough of the signal). The system now met all performance requirements and was ready for the flight simulation test, which is described in Appendix III.

Results

Three problems arose during the flight simulation test; two were due to contamination and one was caused by the feasibility nature of the damper system. At the completion of the tenth flight-profile simulation cycle, the null signal was slightly greater than the failure limit of ±0.075 in.; the null was 0.080 in. Since a commercially available needle valve was used as a trim control, it is believed that under temperature cycling and vibration the valve setting changed, causing the null to change. Upon renulling the output, the system met all performance requirements. Normally, a valve of this type would not be needed in a production system. The null would be adjusted at the time of calibration by fixed orifices.

After the fifteenth cycle, during an attempt to conduct the frequency response test, the system output wave form was very poor, and the shorted hi-pass gain was low. The null position of the actuator between the

shorted hi-pass condition and the hi-pass condition was 0. 250 in.; normally it is only 0. 050 in. Upon disassembly of the straight-through amplifier cascade, a piece of magnesium silicate approximately 0. 035 in. in diameter was found in the power nozzle of the straight-through cascade output amplifier. The performance tests were restarted, but system noise was high and gain was low; therefore, the complete system was disassembled and cleaned. The rate sensor was very dirty. Before the system was rerun, a non-bypassing filter was installed at the system inlet and the filter element on the pump was changed. It is believed that the pump filter was bypassing during all the previous testing, since after changing the filter element the supply pressure was 50 psig less than it had been previously. This is exactly the bypass pressure of the filter. After the twenty-fifth cycle, the system gain exhibited high noise and low shorted hi-pass gain. After a thorough cleaning, satisfactory system performance was again obtained.

The system was then mounted on the life test fixture, which applied a ±45 deg/sec peak rate at 0. 1 cps input frequency. It was subjected to the same environment as the environmental life test components using 10-micron oil. It was necessary to add a number of brackets to tie down the piping to prevent the epoxy joints from breaking. After the system was on the life test fixture for 1158 hours, the null changed sufficiently to be out of specification. Repositioning the nulling needle valve returned the system to proper performance. Again, null shift was considered to be caused by the needle value's moving under the 2-g and 0. 5-g vibration levels imposed upon the system while on the life test fixture. No other problems occurred during the remainder of the life test.

Figure 44 shows the system after it completed 30 cycles of flight simulation and 1158 hours of life test. Figures 45 and 46 are the curves of the performance at the beginning and end of the life test.

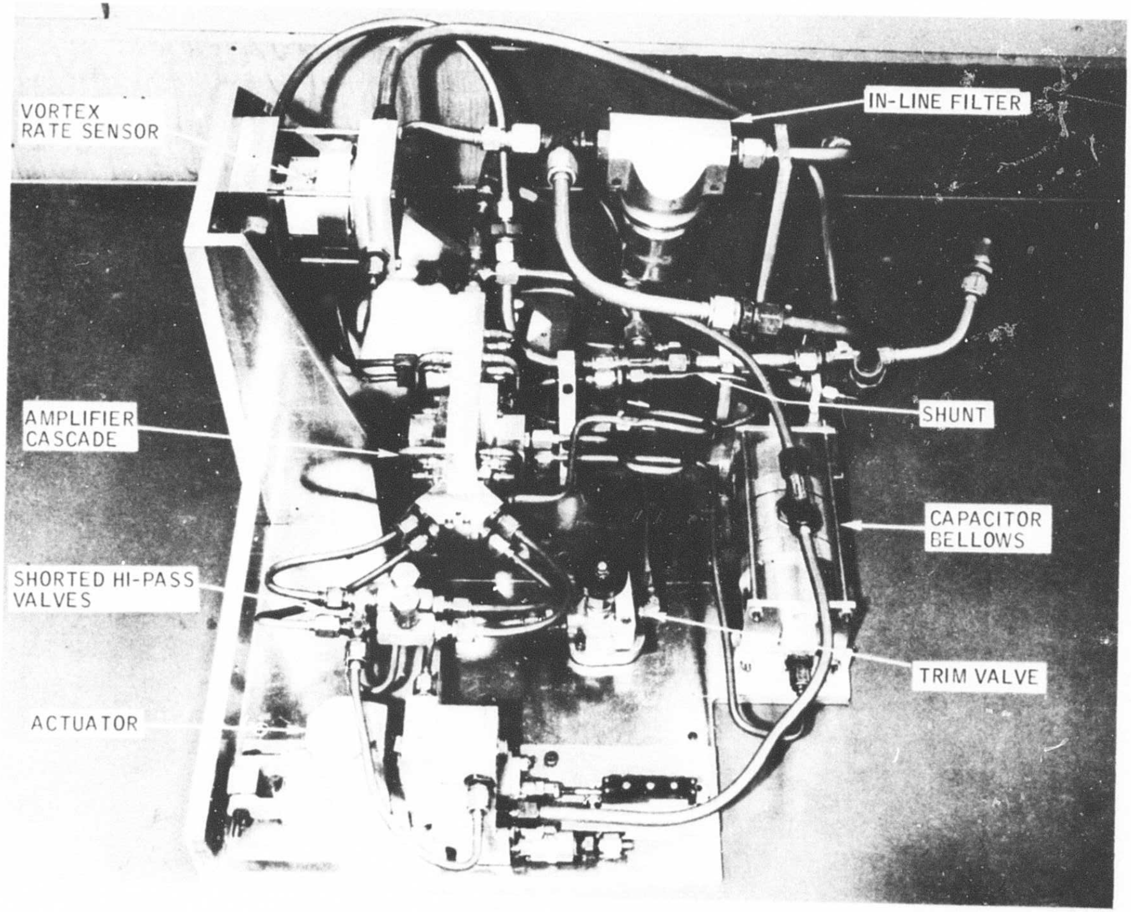


Figure 44. Feasibility System After Completion of Flight Simulation and Life Test.

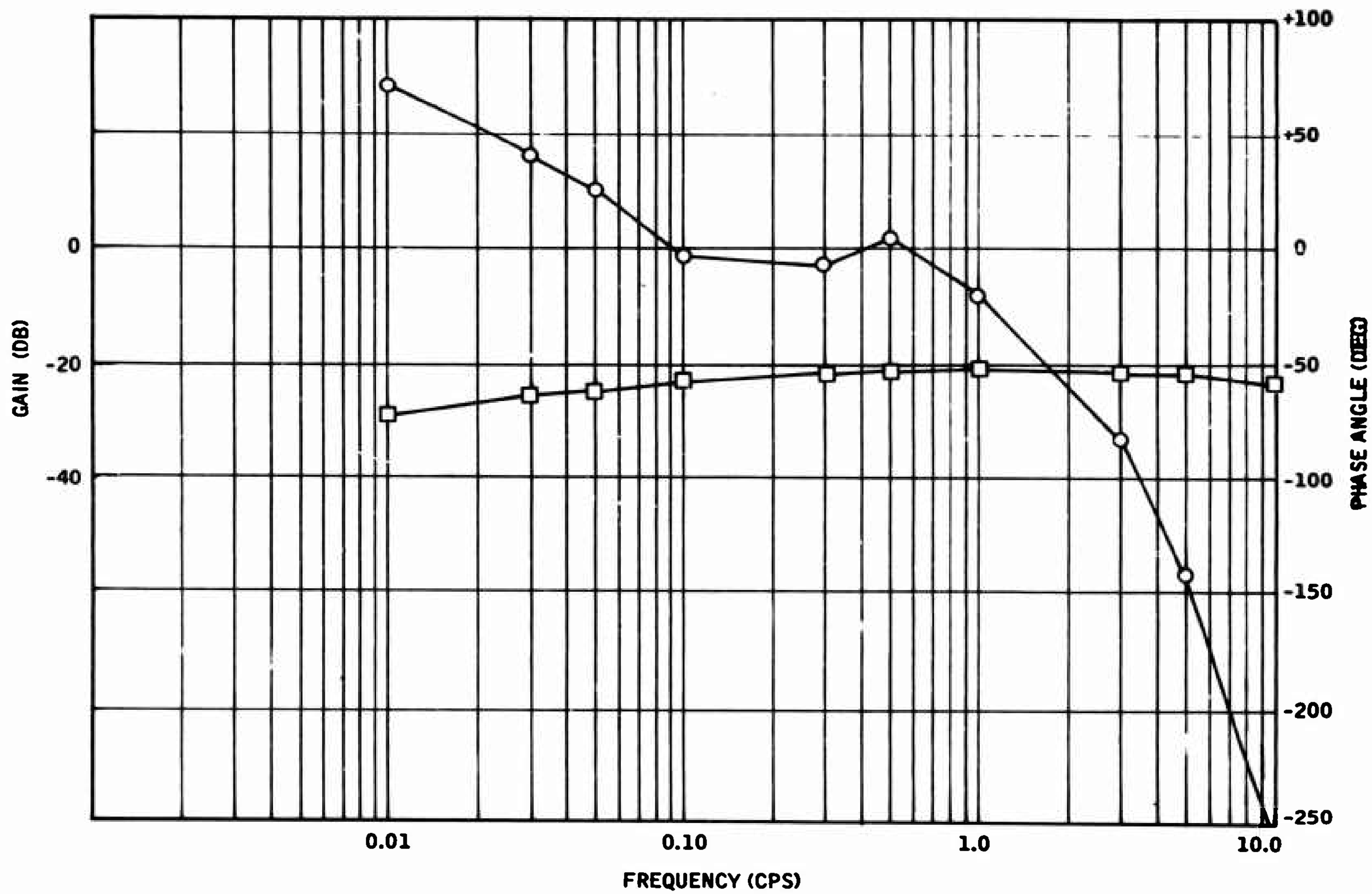


Figure 45. UH-1B System Initial Performance in Life Test.

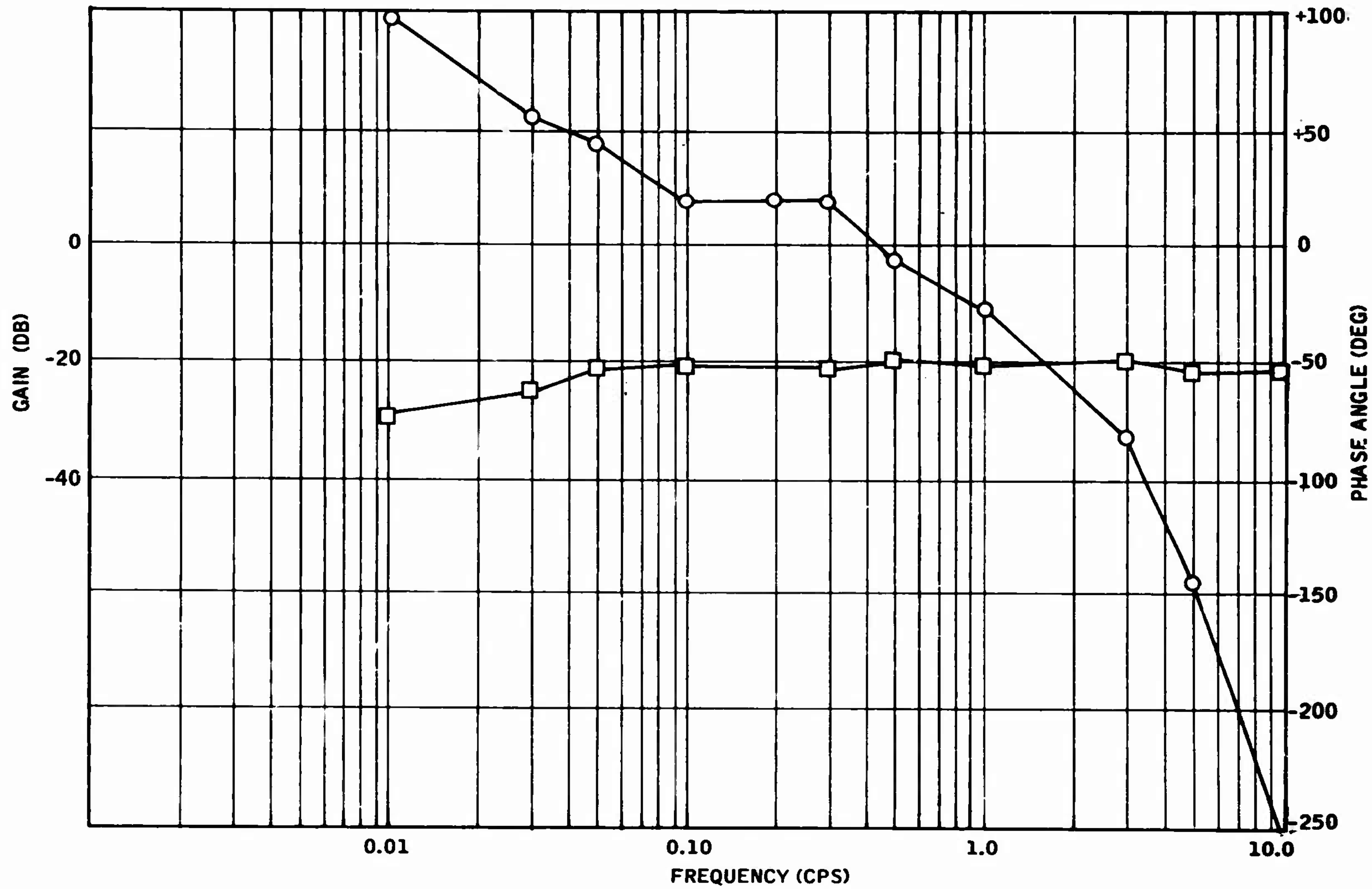


Figure 46. UH-1B System F:nal Performance in Life Test.

APPENDIX I

PLAN FOR LIFE TEST OF HYDRAULIC FLUIDIC COMPONENTS

SUMMARY

The goal of the life test was to obtain 3000 hours of operating time on the feasibility system and 15 sets of components. Each set consisted of one rate sensor, one bistable amplifier, one proportional amplifier, one bellows, and one trim control. The 3000 operating hours were accumulated in twelve 250-hour cycles, with each cycle taking two weeks. Each two-week cycle consisted of four function checks, one performance check, three temperature cycles, and the running time.

The 15 sets of components were divided into three groups of five sets each and were operated under the following conditions:

1. Five sets of components, operated with MIL-H-5606A hydraulic oil under 10-micron filtration, were the non-environmental units. They received no input cycling, no vibration, and no temperature cycling, but they were tested according to the above schedule. These are shown in Figure 47.

2. Five sets of components, operated with MIL-H-5606A hydraulic oil under 10-micron filtration, received the following environments:

    a. Fluid reservoir temperature variation from -30°F to 200°F cycles three times per two-week cycle.

    b. Continuous vibration of 0. 5-g at 20 cps.

    c. The feasibility system and rate sensors received sinusoidal varying rates of ±45 deg/sec peak rate at a frequency of 1 cps.

    d. The amplifiers and bellows continuously cycled from output saturation to saturation at 1 cps.

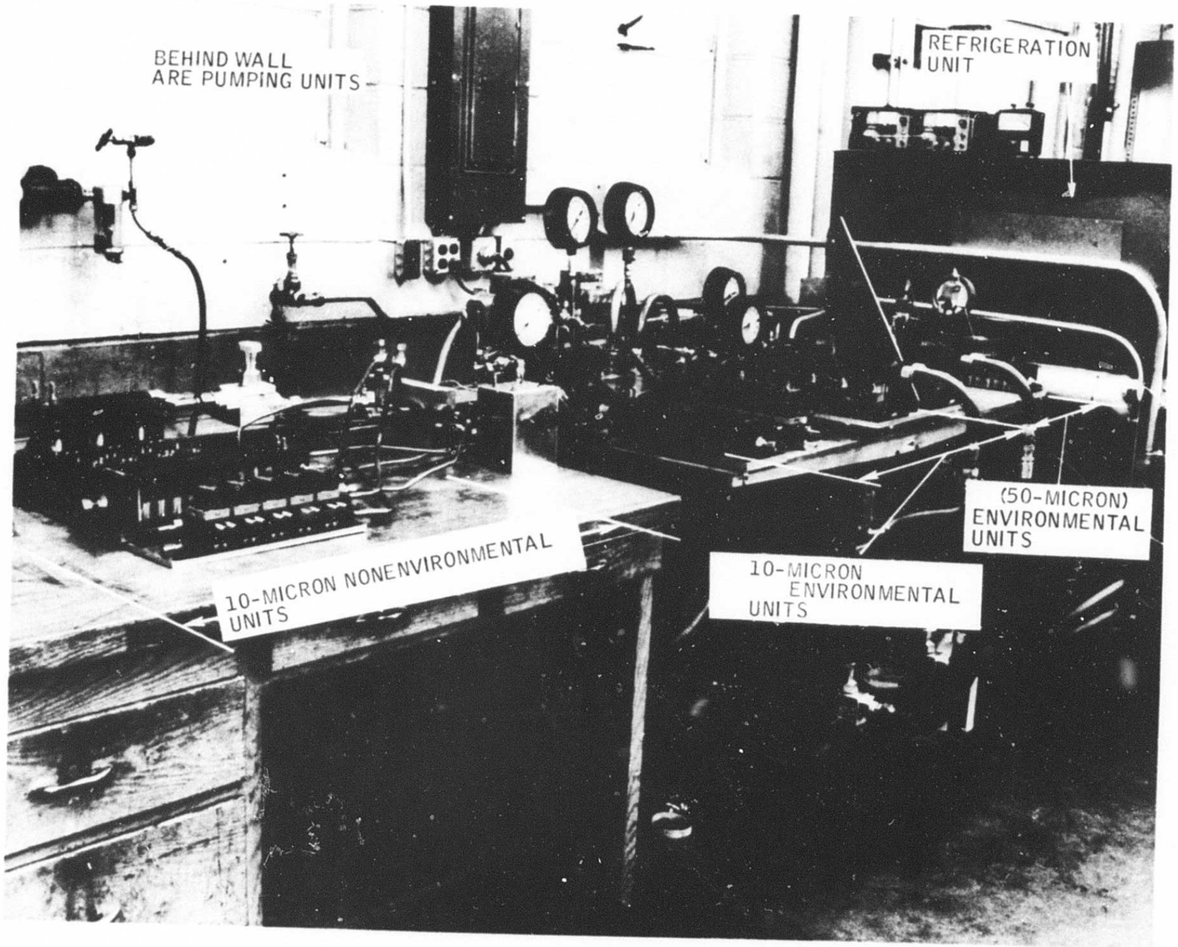


Figure 47. Life Test Components and Fixturing.

e. The trim controls cycled at 1 cps at ±15 volts peak input.

f. During two 4-hour periods of each cycle, the vibration increased to 2-g's at 20 cps for 10 minutes out of each hour.

3. Five sets of components were operated with MIL-H-5606A hydraulic oil under 50-micron filtration. These units experienced the same environments as stated in subparagraphs c through e in the preceding subparagraph. The environmental units are shown in Figure 48.

4. One set of components was kept on the shelf and experienced no testing, unless additional data was wanted.

SCHEDULE

Each test cycle consisted of a two-week period in which approximately 250 running hours were obtained. The daily procedure was as follows:

Sunday	Normal operation
Monday	Functional check
Tuesday	Temperature cycle and four 10-minute periods of high-g vibration exposure
Wednesday	Functional check
Thursday	Temperature cycle and four 10-minute periods of high-g vibration exposure
Friday	Functional check
Saturday	Normal operation
Sunday	Normal operation
Monday	Performance check
Tuesday	Performance check
Wednesday	Performance check

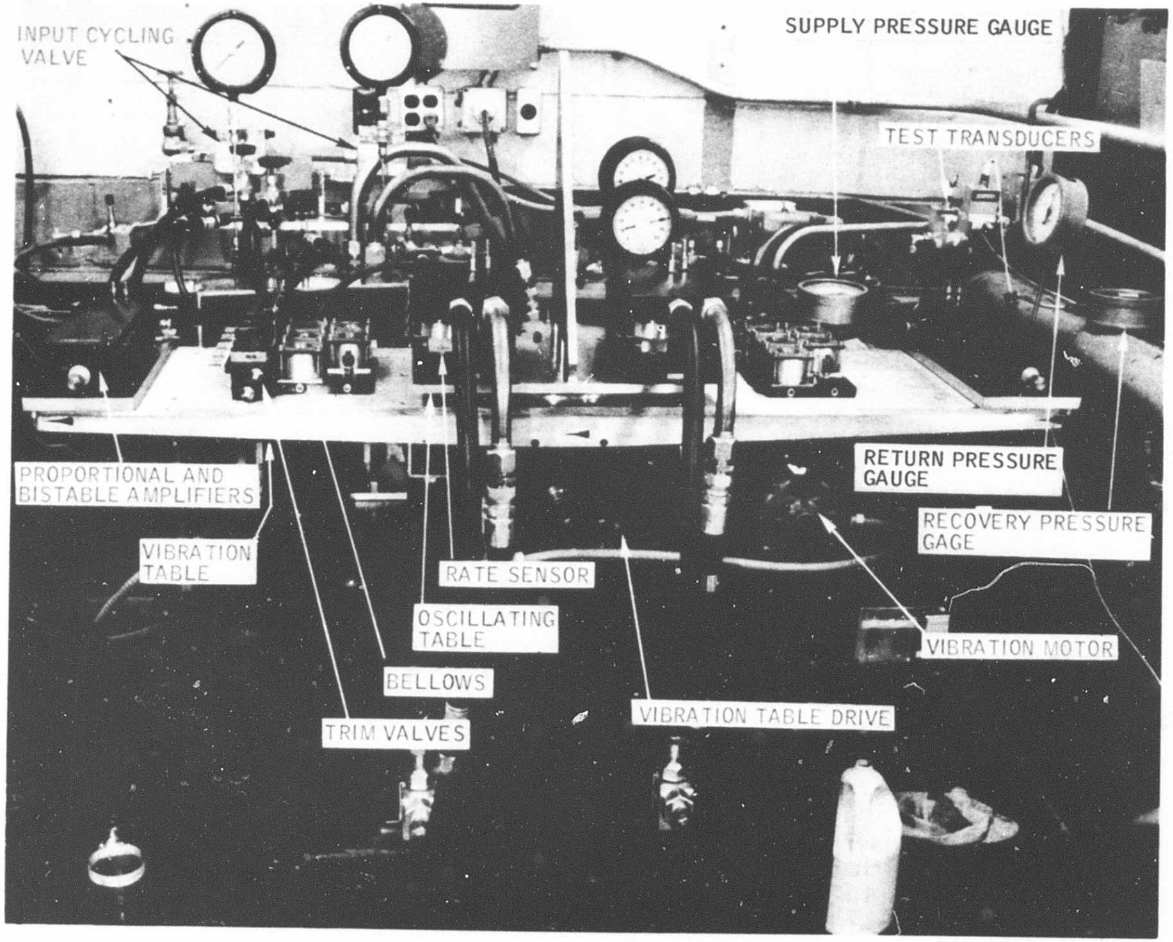


Figure 48. Environmental Units and Fixturing.

Thursday	Temperature cycle
Friday	Functional check
Saturday	Normal operation

All time not used for functional tests, performance tests and temperature cycles was used for normal operation of the life test. The only exception was during performance testing, when the life test was not restarted until the performance test was completed on all units.

NORMAL OPERATION

The normal environmental test setup consisted of two basic systems: a 10-micron filter "clean" oil system and a 50-micron filter "dirty" oil system. Each system had a reservoir with an oil-Freon heat exchanger controlled by the external refrigeration unit and an oil-water heat exchanger controlled by water bypass valves.

The external refrigeration unit contained the ON-OFF controls for the oil-Freon heat exchanger and heat exchanger motors, and the ON-OFF controls for the oil reservoir heaters.

Safety switches were incorporated into the systems to monitor reservoir oil level, oil pressure, and oil temperature. If the oil pressure fell below 175 psig or the oil level fell below a selected point due to leakage, the pump automatically shut down. If the oil temperature exceeded a preset point, the pump stopped. An oil-water heat exchanger controlled the oil temperature at 120°F. Figures 49 and 50 show the pumping units.

The component control valves were adjusted to give the following supply pressures:

Rate sensors	16 psi above return pressure
Amplifiers	10 psi above return pressure
Trim controls	10 psi above return pressure
Bellows	1 psi above return pressure

The yaw-and-vibrator table was set for 0.5-g vibration. A timer was used to control the cycle units during normal operation.

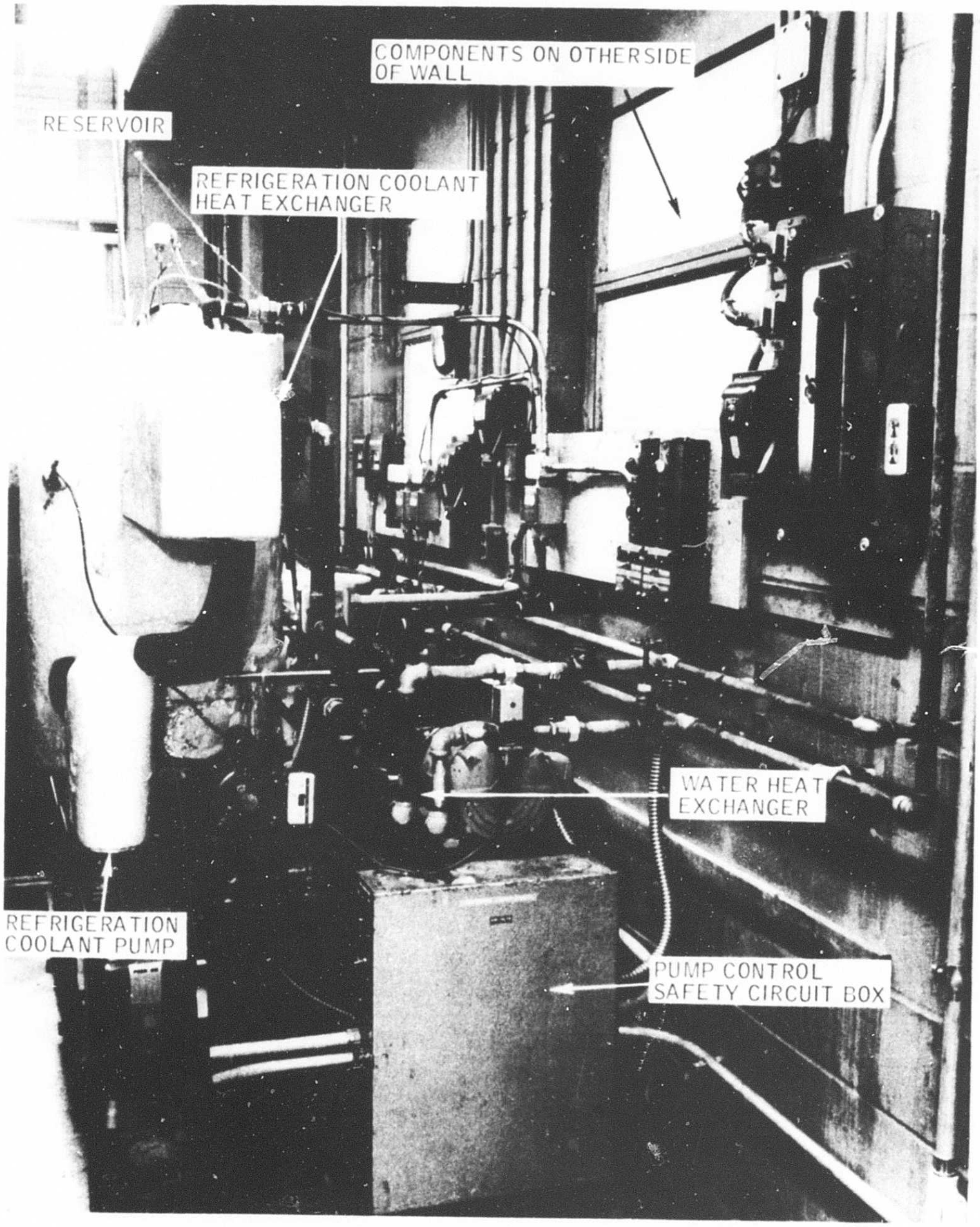


Figure 49. Pumping Units and Electrical Controls.

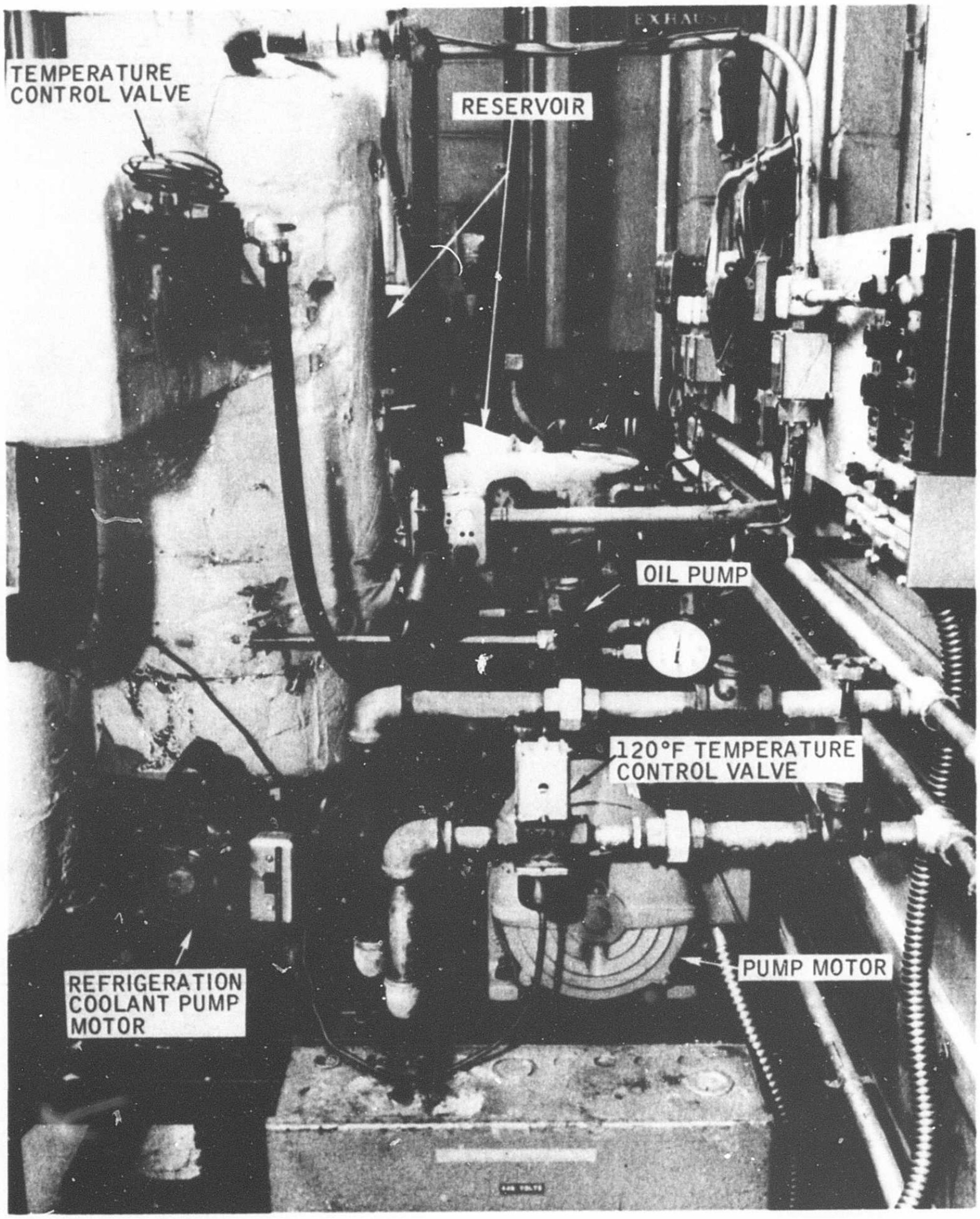


Figure 50. 50-Micron and 10-Micron Pumping Units with Environmental Fixturing.

TEST PROCEDURE

Functional Check

With the life test in normal operation at 120°F fluid temperature and the yaw-and-vibration table and "cyclers" turned off, the system and components were tested per the following procedure:

System

1. Set flow to the feasibility system at 2.86 gpm.
2. Place 30 vdc across the system actuator potentiometer. Connect output to Sanborn recorder and null.
3. Mount electronic rate gyro on yaw table and excite with 20-v, 400-cps power. Connect output of gyro demodulator into two-channel Sanborn recorder.
4. Place 1000 psi on the actuator.
5. Record system null. Turn on yaw table and record rate input and actuator output.

Rate Sensor - Environmental Units

1. Set supply pressure to the rate sensor manifolds at 16 psi above return pressure.
2. Place electronic rate gyro on yaw table. Connect rate gyro output into Sanborn recorder.
3. Connect output of ±5 psid pressure transducer to Sanborn recorder.
4. Connect transducer to output of rate sensor and close shutoff valves on rate sensor. Bleed pressure transducer.
5. Measure sensor null on Sanborn recorder.
6. Turn on yaw table and record rate input and differential pressure output.
7. Turn off yaw table, remove transducer from sensor, and open sensor shutoff valves.

8. Repeat steps 4 through 7 for each of the remaining rate sensors.

Rate Sensor Non-Environmental Units

1. Place the ±5 psid pressure transducer on the output of the rate sensor. Close the rate sensor shutoff valves and bleed the transducer.

2. Record the null per steps 3 and 5 of preceding procedure.

3. Remove transducer and insert pressure gauge in right output port of rate sensor. Record pressure level and return pressure.

4. Remove pressure gauge and open sensor shutoff valve.

5. Repeat steps 1 through 4 for each of the remaining rate sensors.

Amplifiers

The following functional checks were completed on all 30 proportional and bistable amplifiers and consisted of drawing the amplifier gain curve with an x-y plotter. Figure 51 shows amplifier testing during a functional check.

1. Connect the ±5 psid pressure transducer to the x-y plotter vertical axis and ±10 psid pressure transducer to the x-y plotter horizontal axis.

2. Check transducer calibration.

3. Connect the ±5 psid transducer to the control ports of the amplifier manifold and the ±10 psid transducer into the output ports.

4. Close the amplifier input signal control flow valves.

5. Set the amplifier supply pressure at 10 psi above return pressure.

6. Set the amplifier control pressures at 1.5 psig above return pressure.

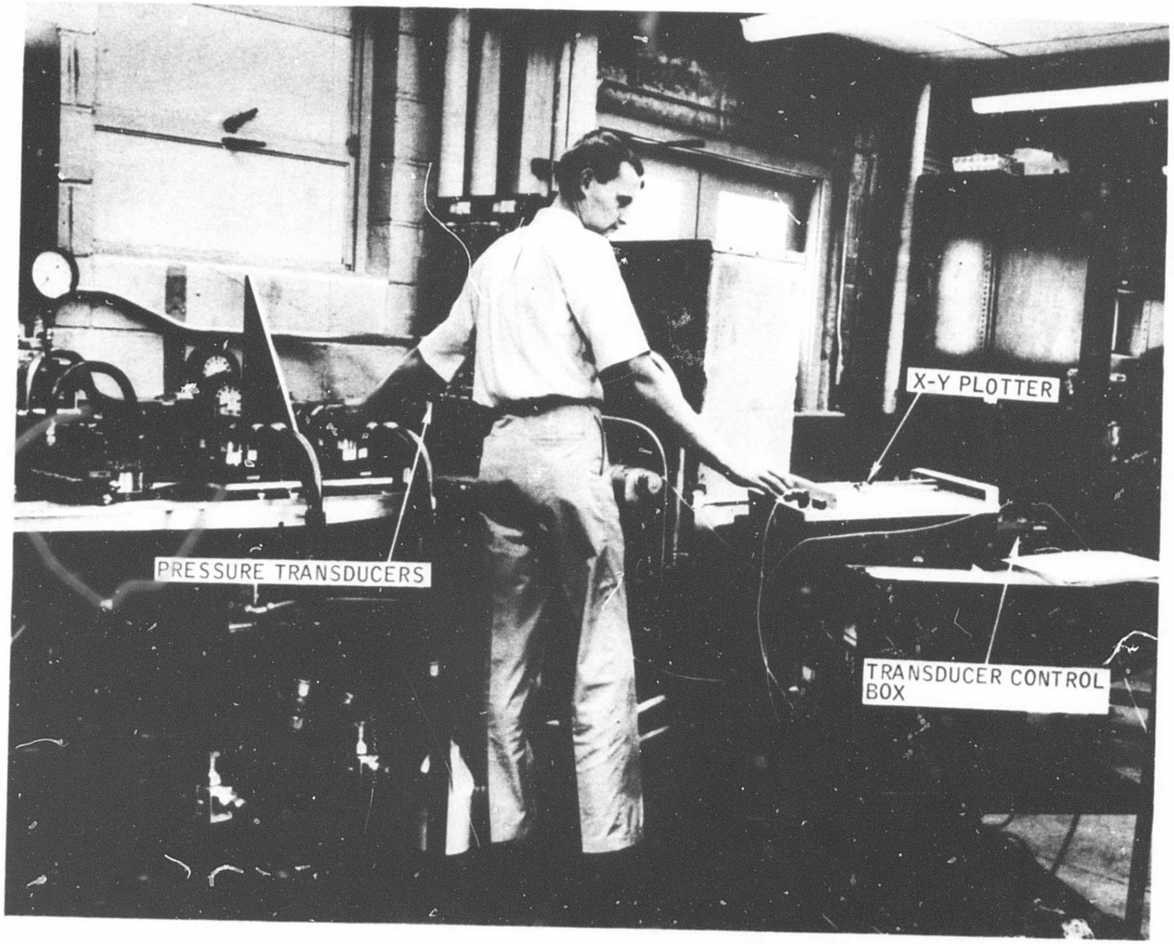


Figure 51. Amplifier Functional Checks.

7. Draw amplifier gain curve.

8. Repeat procedures 1 through 7 for each remaining amplifier.

Trim Controls

The functional check included all 15 trim controls and consisted of drawing the gain curve of voltage input versus differential pressure output. The steps were:

1. Set supply pressure at 10 psi above return pressure.

2. Turn switch on trim control function box to manual.

3. Connect output of trim control function box to trim controls and to input axis of x-y plotter.

4. Connect ±10 psid transducer to output axis of plotter, null, and calibrate.

5. Connect transducer to trim control and close shutoff valves.

6. Lift plotter pen and place ±15 volts on trim control by moving voltage control knob on trim control function box.

7. Drop pen and draw gain curve from +15 v to -15 v by moving voltage control knob.

8. Open shutoff valves and remove transducer.

9. Repeat steps 6 through 9 for each of the remaining trim controls.

Bellows

The functional check included all 15 bellows and consisted of drawing the curves of pressure versus deflection. The steps were:

1. Connect 0-10 psi pressure transducer to input axis of x-y plotter and null. Check transducer calibration.

2. Connect 6.0 vdc to displacement transducer and connect output to plotter output axis.

3. Close pressure valve.

4. Turn three-way return valve to vent return into ambient container.

5. Close return valve to within quarter turn of closure.

6. Place pressure transducer on bellows manifold.

7. Place displacement transducer on bellows to be tested.

8. Open pressure valve and draw gain curve from 0 to 2 psi.

9. Lift pen and close pressure valve.

10. Repeat steps 7 through 9 for each remaining bellows.

Performance Check

Flow to all components, except those being tested, was turned off. Fluid temperature was set at 120°F; yaw, vibration, and cycles were turned off. The system and components were tested per the following procedure:

System

1. Remove the system from the yaw table and mount on oscillating table. No disconnecting of the hoses necessary.

2. Set total system flow for 2.86 gpm.

3. Check amplifier supply pressure and adjust to 5 psi above return pressure if necessary.

4. Place 30 vdc across system actuator potentiometer and connect output to Sanborn recorder. Null the readout with no pressure to the actuator and then place 1000 psi on the actuator.

5. Mount electronic rate gyro on oscillating table and connect output to Sanborn recorder.

6. Connect function generator into oscillating table servo-amplifier and place 30 vdc on the servo-amplifier.

7. Connect auxiliary hydraulic power supply to oscillating table actuator and set to 2000 psi.

8. Turn on power to the servo-amplifier and engage "engage" and "servo" switches.

9. Program a sinusoidal ±2 deg/sec peak rate input to the oscillating table at the following frequencies: 0.01, 0.03, 0.05, 0.10, 0.30, 0.50, 1.0, 3.0, 5.0, and 10.0 cps. Record the input rate and the system actuator output.

10. Close the system output valves for shorted hi-pass condition.

11. Vary the system flow from 2.73 to 2.99 gpm and monitor the resulting system actuator output.

12. Open the system output valves and replace the system on the yaw and vibrator table.

Rate Sensors

All 15 rate sensors were subjected to the following tests:

1. Mount manifold consisting of five rate sensors on rate table. Connect flowmeter on return line from rotating joint. Note: Separate flowmeters are used for the 10-micron and 50-micron oil systems, respectively.

2. Connect ±5 psid pressure transducer to output axis of x-y plotter. Null and calibrate transducer.

3. Mount rate gyro on rate table and connect demodulator output to input axis of x-y plotter. Place 60 deg/sec rate into the rate gyro and set rate input by strobe on rate table. Adjust x-y plotter gain, and adjust the zero point as necessary.

4. Set total manifold flow to 11.0 gpm. Record sensor package supply and return pressures.

5. Place transducer on rate sensor to be measured, and close sensor shutoff valves.

6. Place 60 deg/sec CW rate into sensors and record output.

7. Slowly decrease rate to zero, and then increase in CCW direction to 60 deg/sec.

8. Change output of pressure transducer from x-y plotter to Sanborn recorder.

9. Bleed transducer and monitor noise on Sanborn.

10. Lower total sensor package flow to 10.0 gpm and record sensor null as total flow is changed from 10.0 to 12.0 gpm.

11. Open sensor shutoff valves and remove pressure transducer.

12. Repeat steps 4 through 11 for each of the remaining sensors.

Amplifiers

The following performance test was conducted on all 30 amplifiers:

1. Close power flow valve, return valve, and both control valves.

2. Remove amplifiers from manifold.

3. Connect proper flowmeter to power flow valve and exhaust flowmeter into graduated cylinder. There are separate flowmeters for the 10-micron and 50-micron systems.

4. Calibrate flowmeters.

   a. Open power flow valve until flowmeter reads about 12 on the scale. Allow fluid temperature to stabilize to 117°F as measured by thermocouple near flowmeters.

Measure flow to the graduated cylinder for one minute. Calculate flow rate (in.^{3}/min) for this flowmeter reading.

b. Repeat step a for flowmeter readings of about 13 and 15.

c. Draw curve of flowmeter reading versus flow rate. This curve should be constant but must be checked before each performance test.

d. Flowmeters for both the 10-micron and 50-micron systems must be calibrated.

5. Place large aluminum spacer block and gasket in manifold and replace manifold top.

6. Put amplifier to be tested in manifold.

7. Open amplifier shutoff valves.

8. Open power flow valve until a flow of 14.5 in.^{3}/min is reached for the proportional amplifiers and 11.0 in.^{3}/min for the bistable amplifiers.

9. Connect, calibrate, and bleed pressure transducers and set amplifier input signal control pressure to 1.5 psi above return pressure. Follow steps 1 through 7 of amplifier functional check procedure.

10. Record noise of amplifier output on Sanborn recorder.

11. Null output of amplifier and measure pressure level of amplifier output. Record this pressure level and supply and return pressures.

12. Repeat step 9 using power flows of 13.5 and 15.5 in.^{3}/min for the proportional amplifiers and 10.0 and 12.0 in.^{3}/min for the bistable amplifier. Omit noise and pressure measurements during these tests.

13. Close amplifier shutoff valves and remove amplifier from manifold.

14. Repeat steps 6 through 13 for the remaining nine amplifiers in the manifold. Then replace all amplifiers in the manifold.

15. Test other amplifiers in remaining manifolds per the preceding steps.

Trim Controls

The procedure for the performance check on all trim controls is identical to that of the functional check, with the following two additions:

1. Gain curves will be drawn at supply pressures of 8 and 12 psi above return pressure in addition to the nominal 10 psi.

2. With the supply pressure set at 10 psi above return pressure, and the output differential pressure nulled, the output pressure level and the return pressure shall be recorded.

Bellows

The procedure for the performance check on all 15 bellows is identical to the functional check described previously.

DATA ANALYSIS

Data were obtained during the functional and performance tests. Functional checks were used only for indications of component function; hence, only a few parameters of each component were measured. No data analysis was performed on the functional test data. It was intended only to show gross changes in a component which were readily apparent apparent from a gain curve.

Performance checks were more comprehensive and data analysis was more detailed. The following information lists the parameters that were measured, analyzed, and recorded for each component.

System

From the strip-chart recording, the phase lag and amplitude ratio were determined for each frequency. A plot of phase lag and amplitude ratio (db) versus frequency was then made. Also, noise, null, and null shift versus supply flow variation were recorded.

Rate Sensors

From the gain plot and strip-chart recording, the following data were analyzed and recorded:

1. Scale factor (psi/deg/sec)

2. Linearity (percent of full-scale output in ±60 deg/sec input range)

3. Null (percent input shift of ±60 deg/sec input range)

4. Noise (psi)

5. Null versus supply flow (psi)

Proportional Amplifiers

The data recorded at the nominal flow conditions were analyzed, and the following parameters were recorded. No data were analyzed from the high and low flow conditions.

1. Supply flow ($in.^3/min$)

2. Scale factor (psi/psi)

3. Linearity (percent of ±4 psi output range)

4. Linear range (total psi range within linearity determined from step c)

5. Null (percent of 8 psi output)

6. Noise (psi)

7. Pressure recovery (psi)

Bistable Amplifiers

The performance at the nominal flow condition was analyzed and recorded. No data were analyzed from the low and high flow conditions.

1. Supply flow (in.^{3}/min)

2. Pressure gain (psi/psi)

3. Switching threshold (± psi)

4. Null (mean pressure between switching thresholds expressed as a percent of supply pressure)

5. Noise (percent of output range)

6. Pressure recovery (psi)

Trim Control

Trim control data was analyzed only on the 10-psi supply pressure data. No analysis was done on the data taken at 8 and 12 psi supply pressures. The following parameters were analyzed:

1. Supply pressure (psi)

2. Scale factor (psi/volt)

3. Pressure level (psi)

4. Null (percent of 15 v input)

Bellows

The following parameters were determined from the gain curves:

1. Nominal deflection (bellows deflection in inches at 1 psi pressure)

2. Scale factor (in./psi)

The analyzed data were then compared to the component failure criteria. The failure criteria are listed in Appendix II of this report.

LIFE TEST MAINTENANCE

To assure continuous operation of the life test, the following steps were followed:

1. Check filters every other day to assure that they are not bypassing. Clean if necessary.

2. Make sure pump safety circuit is engaged for all unattended running (overnight and weekends).

3. Check periodically to assure fluid temperature is maintained at 120°F.

4. Fix all leakage if possible.

5. If components are leaking, inform design personnel of any desired action.

6. Make sure all instrumentation is in calibration. If not, make provisions for calibration of instrumentation.

7. Every other cycle, fluid samples shall be drawn from the clean and dirty oil system and brought to Material Engineering for contamination test. Contamination should be consistent with previous samples.

DOCUMENTATION REQUIREMENTS

All data were placed in either the Function Check Data Book or the Performance Check Data Book. Analyzed data were logged in on Performance Test Data forms. All failures were documented on the Failure Report Form and placed in the failure report log book.

A Life Test Log Book was kept for daily entries on work performed on the life test, hours run, and any special problems or occurrences.

INSTRUMENTATION AND READING ACCURACY

The accuracy of the instrumentation and the ability to read the instruments and curves used to test the components and system are dependent upon the parameter that is being measured. Table VIII shows the accuracy of each parameter measured for the various components.

TABLE VIII. INSTRUMENTATION ACCURACY

Component and Measured Parameter	Accuracy % of Full Scale	Reading Accuracy % of Full Scale	Total Accuracy % of Full Scale
Vortex Rate Sensor			
Supply Flow	±1.0	±0.5	±1.50
Supply Pressure	±0.75	±0.5	±1.25
Linearity	±2.72	±1.0	±3.72
Scale Factor	±2.72	±2.0	±4.72
Null	±1.62	±1.0	±2.62
Proportional Amplifier			
Supply Flow	±1.0	±0.5	±1.50
Pressure Recovery	±0.75	±0.5	±1.25
Linearity	±3.39	±1.0	±4.39
Scale Factor	±3.39	±1.0	±4.39
Null	±1.83	±0.5	±2.33
Trim Control			
Supply Pressure and Pressure Level	±0.75	±0.5	±1.25
Scale Factor	±1.82	±0.5	±2.32
Null	±1.42	±0.5	±1.92
Bellows			
Nominal Deflective	±1.16	±0.3	±1.46
Scale Factor	±1.16	±0.5	±1.66
Bistable Amplifiers			
Supply Flow	±1.0	±0.5	±1.50
Pressure Recovery	±0.75	±0.5	±1.25
Pressure Gain	±4.83	±1.5	±6.33
Null and Switching Threshold	±1.85	±0.1	±1.95

APPENDIX II

FAILURE LIMITS DURING LIFE TEST OF SYSTEM AND COMPONENTS

SYSTEM FAILURE LIMITS

Summary

Analytical studies of UH-1B dynamics and yaw damper effects, conducted on Contract DA 44-177-AMC-294 (T), were used to establish overall system failure criteria.

In order to equate system failure criteria to component criteria, specific system mechanizations were analyzed and component failure limits were determined by assessing the effects of component variations on the overall system performance. Two system mechanizations were analyzed; the UH-1B feasibility system and a selected future typical system. Failure limits were established for the following parameters:

- Scale factor
- Phase angle
- Range
- Noise level
- Null shift
- Linearity
- Threshold

The failure criteria that were applied to the feasibility system are presented in Table IX. These failure criteria were applicable during the flight profile simulation and life test programs.

TABLE IX. SYSTEM FAILURE CRITERIA	
Performance Parameter *(Hi-Pass Disconnected)	Failure Limit
Phase Angle @ 1 cps	50-deg lag
Amplitude Ratio @ 1 cps	±36.0% change
*Range (Actuator displacement from center)	±0.30 in.
*Linearity	±15% change
*Threshold	0.1 deg/sec
*Noise (Actuator displacement)	±0.02 in.
*Scale Factor	±36.0% change
*Null Shift (Actuator displacement from center)	±0.075 in.

System Performance Criteria

The system performance limits established are:

- Provide short-period UH-1B helicopter yaw stability augmentation by increasing the vehicle equivalent second-order damping ratio from 0.30 to 0.60 or greater.
- Minimize damper opposition to pilot commands during steady-state maneuvers.

Feasibility System Failure Limits

Failure limits were applied to the system performance parameters using the feasibility system as an analytical model (Reference USAAVLABS Technical Report 66-87, "Fluid State Hydraulic Damper").

Scale Factor (Amplitude Ratio)

It was determined, during feasibility testing, that a system scale factor of 0.14 ± 0.05 degree rotor/degree/second would give satisfactory system performance while providing a damping ratio of 0.60 or greater. This is an allowable scale factor range of ±36 percent. Therefore, the system scale factor failure limit was established as a change of ±36 percent from the initial value.

Phase Angle

Feasibility system testing indicated that, during normal system operation, the phase lag at 1.0 cps was approximately 40 degrees. Checking the phase angle will give information on changes in system hydraulic lags. Therefore, the phase angle failure limit was established at a 50-degree lag at 1.0 cps.

System Authority

The system authority or output range is effectively defined in terms of the servo actuator displacement. System analysis indicated that 80 percent of the displacement range of the servo actuator, or ±0.300 in., was required to damp external disturbances effectively. The system range (authority) failure limit was established at ±0.300 in. of actuator displacement from the center position.

Noise Level

It was determined through analysis of aircraft dynamics that noise in the form of random excursions of the servo actuator must be limited to a level equivalent to actuator displacements of ±0.020 in. Therefore, the noise failure limit was established at ±0.020 in. of actuator displacement.

Null

Null shifts effectively reduce system range or authority and, therefore, are allowable only to the point where the required system range is no longer achieved. Based on the system range requirement, the allowable null shift is equal to 20 percent of the actuator

travel from center to either stop, or a displacement of 0.075 in. The null failure limit was established at an actuator displacement of ±0.075 in.

Linearity

To maintain a reasonable constant loop gain over the system range, a linearity failure limit of a change of ±15.0 percent from the initial value was established for the damper system.

Threshold

The system threshold is basically determined by the threshold of the actuator, which is equivalent to a yaw rate of 0.10 degree per second. The system threshold failure limit was established at 0.10 degree per second. However, due to the interaction of noise and threshold, the effective system threshold may actually be determined by the noise level.

Future System Failure Limits

The following failure limit determinations are based on the selected future system mechanization.

Scale Factor

The future system has three gain elements:

- Rate sensor
- Preamplifier
- Amplifier

This system has an integral scale factor change capability of ±40 percent, which can be added to the allowable system scale factor change of ±36 percent. The resulting 76-percent scale factor change allowance will be apportioned to the three elements.

Linearity

The linearity failure limit is unchanged from the feasibility system.

Null

Null offsets in the sensor or preamplifier effectively reduce the dynamic ranges of the bellows. Therefore, offsets which do not reduce the required dynamic range are allowable. Including

consideration of the 20.0-percent allowable scale factor change, the allowable null shift can be apportioned at ±30.0 percent of the component output range. The null failure limit was established at ±30.0 percent of range change from the initial value.

Threshold

The threshold failure limit is unchanged from the feasibility system.

Noise

The noise failure limit remains the same as for the feasibility systems.

COMPONENTS FAILURE LIMITS

The failure limits presented in Table X were established from the following considerations. The system failure criteria upon which the component limits were derived are presented under the paragraph on System Failure Limits. Criteria for the two-system configurations were considered: the feasibility system to be life tested and the system configuration considered most likely to be used in future development programs.

Feasibility System

The following failure limit determinations are based on the feasibility system mechanization.

Scale Factor

The feasibility system has four gain elements:

- Rate sensor
- Preamplifier
- 'rst hi-pass amplifier
- Second hi-pass amplifier

The allowable system scale factor change of ±36 percent was apportioned equally to the four elements. The scale factor failure limit for each component was established at a change of ±8.0 percent from the initial value.

TABLE X. COMPONENT FAILURE CRITERIA

Component	Failure Criteria		
	Performance Parameter	Failure Limit	
		First	Second
Rate Sensor	Linearity	±8.0% change	±10.0% change
	Noise (Monitored)	-	-
	Scale Factor	±8.0% change	±20.0% change
	Null (Percent of range)	±5.0% change	±30.0% change
Proportional Amplifier	Linearity	±8.0% change	±10.0% change
	Noise (Monitored)	-	-
	Scale Factor	±8.0% change	±20.0% change
	Null (Percent of range)	±5.0% change	±30.0% change
Bellows	Deflection (Deflection vs pressure)	±20.0% change	±20.0% change
Trim Control	Null (Percent of rated input)	±90.0% change	±90.0% change
Bistable Amplifier	Noise (Monitored)	-	-
	Pressure Gain	±25.0% change	±25.0% change
	Null (Percent of supply pressure)	±1.0% change	±1.0% change

Linearity

The system linearity was apportioned equally to the four gain elements. The linearity failure limit was established at a change of ±8.0 percent of the initial value for each component.

Null

The system range requirement of ±0.300 in. of actuator travel is equivalent to an output amplifier range of ±1.6 psid. Null offsets are allowable to the point where the amplifier output range is reduced to ±1.6 psid from its normal range of ±4.8 psid, or an output level null shift of ±3.2 psid. Including consideration of the 8.0 percent allowable gain change, the allowable null shift can be apportioned at ±5.0 percent of the component output range. Therefore, the null failure limit was established at ±5.0 percent of range change from the initial value.

Noise

Presently, there is not enough data available to permit the system noise requirement to be apportioned to the system components. Therefore, the component noise levels will be monitored until such data are available.

Time Constant

The system time constant is a function of amplifier port resistance and bellows capacitance. Amplifier port resistance changes result in amplifier gain changes which have failure limits established. Bellows capacitance change is a function of the bellows deflection. Half of the allowable system time constant range was assigned to the bellows. The bellows time constant failure limit was established at a deflection change of ±20 percent from the initial value.

Future System

The following failure limit determinations are based on the selected future system mechanization.

Scale Factor

The future system has three gain elements:

- Rate sensor
- Preamplifier
- Amplifier

The 76-percent system scale factor change allowance was apportioned equally to the three gain elements. The scale factor failure limit was established at a change of ±20 percent from the initial value for each component.

Linearity

The system linearity was apportioned equally to the three gain elements. The linearity failure limit was established at a change of ±10.0 percent from the initial value for each component.

Null

Null offsets in the sensor or preamplifier effectively reduce the dynamic range of the bellows. Therefore, offsets which do not reduce the required dynamic range are allowable. Including consideration of the 20.0-percent allowable scale factor change, the allowable null shift can be apportioned at ±30.0 percent of the component output range. The null failure limit was therefore established at ±30.0 percent of range change from the initial value.

Noise

The noise failure limit remains the same as for the feasibility system.

Time Constant

The time constant failure limit is unchanged from the feasibility system.

SUPPLEMENTAL EQUIPMENT

The following failure limit determinations are based on projected application requirements.

Trim Control

A null calibration device is the projected application of trim control. Therefore, the null failure limit was established at a change of ±90.0 percent of the rated input.

Bistable Amplifier

The following failure limits were established on the basis of projected circuit requirements:

Noise

The noise level will be monitored, as available data do not permit a reasonable failure limit to be established.

Pressure Gain

The pressure gain failure limit was established at a change of ±25.0 percent from the initial value.

Null

The null failure limit was established at a change of ±1.0 percent of supply pressure from the initial value.

APPENDIX III

FLIGHT SIMULATION TESTS OF FEASIBILITY YAW STABILITY AUGMENTATION SYSTEM

PROCEDURE

Summary

The purpose of the flight simulation tests was to subject the UH-1B yaw stability augmentation system (SAS) to thirty 2-hour tests. Each test simulated flight conditions at both -25°F and +100°F ambient temperatures with continuous yaw input and vibration exposure. Initially, and at the completion of every five tests, the SAS was tested at nominal controlled conditions to determine any variance in SAS performance. Failure criteria based on the initial performance data were used to determine any SAS failures.

Closed-Loop Test

At the start and completion of the flight simulation tests, closed-loop tests were performed on the system. The test procedure and setup are explained in Chapter 5 of USAAVLABS Technical Report 66-87, "Fluid State Hydraulic Damper". This test was to verify the augmentation of the UH-1B SAS.

Performance Test

Initially, and after the completion of every five cycles, a performance test was conducted to check the function of the SAS. The SAS was operated under the following conditions:

1.	Fluid Temperature	120°F
2.	Total System Flow	2. 86 gpm
3.	Amplifier Supply Pressure	5 psi above return pressure

The following tests were performed on the SAS:

Frequency Response

The SAS was mounted on the oscillating table and subjected to a +2 deg/sec sinusoidal peak rate input from 0.01 cps to 10.0 cps. The phase angle and amplitude ratio were determined at 0.01, 0.03, 0.05, 0.10, 0.30, 0.50, 1.0, 3.0, 5.0, and 10.0 cps.

Steady-State Test

The SAS, in the shorted hi-pass condition, was mounted on a rate table, and an x-y plot of rate input versus SAS actuator output was drawn. Scale factor and linearity were determined from the plots.

Null Shift Versus Supply Pressure

With the SAS in the shorted hi-pass condition, the system flow was varied from 2.75 gpm to 3.00 gpm, and the resulting SAS actuator deflection was recorded.

Test Cycle

Each test cycle was of 2 hours' duration and consisted of varying ambient and fluid temperatures according to the profile shown in Figure 52. In addition to temperature variations, the SAS was exposed to continuous 0.5g-20 cps vibration and ±45 deg/sec peak sinusoidal yaw rate at 1 cps. A constant differential pressure was held across the system during the test cycle and corresponded to that differential pressure required for 2.86 gpm flow through the system at 120°F fluid temperature. Recordings were made of oscillating table displacement and SAS actuator output every 10°F of fluid temperature rise.

Test Setup

The SAS, mounted on the oscillating table, was placed in a temperature chamber along with the hydraulic pumping unit. Oil was filtered with a 10-micron filter placed in the pressure line. The cold ambient temperature was used to cool the fluid to -25°F through an air-to-liquid heat exchange. Immersion heaters, controlled by a temperature controller, increased the fluid temperature according to the profile shown in Figure 52. Vibration was provided by an eccentric weight driven by an electric motor mounted on the oscillating table. Oscillating table and SAS actuator output were measured with potentiometers and recorded on a Sanborn recorder.

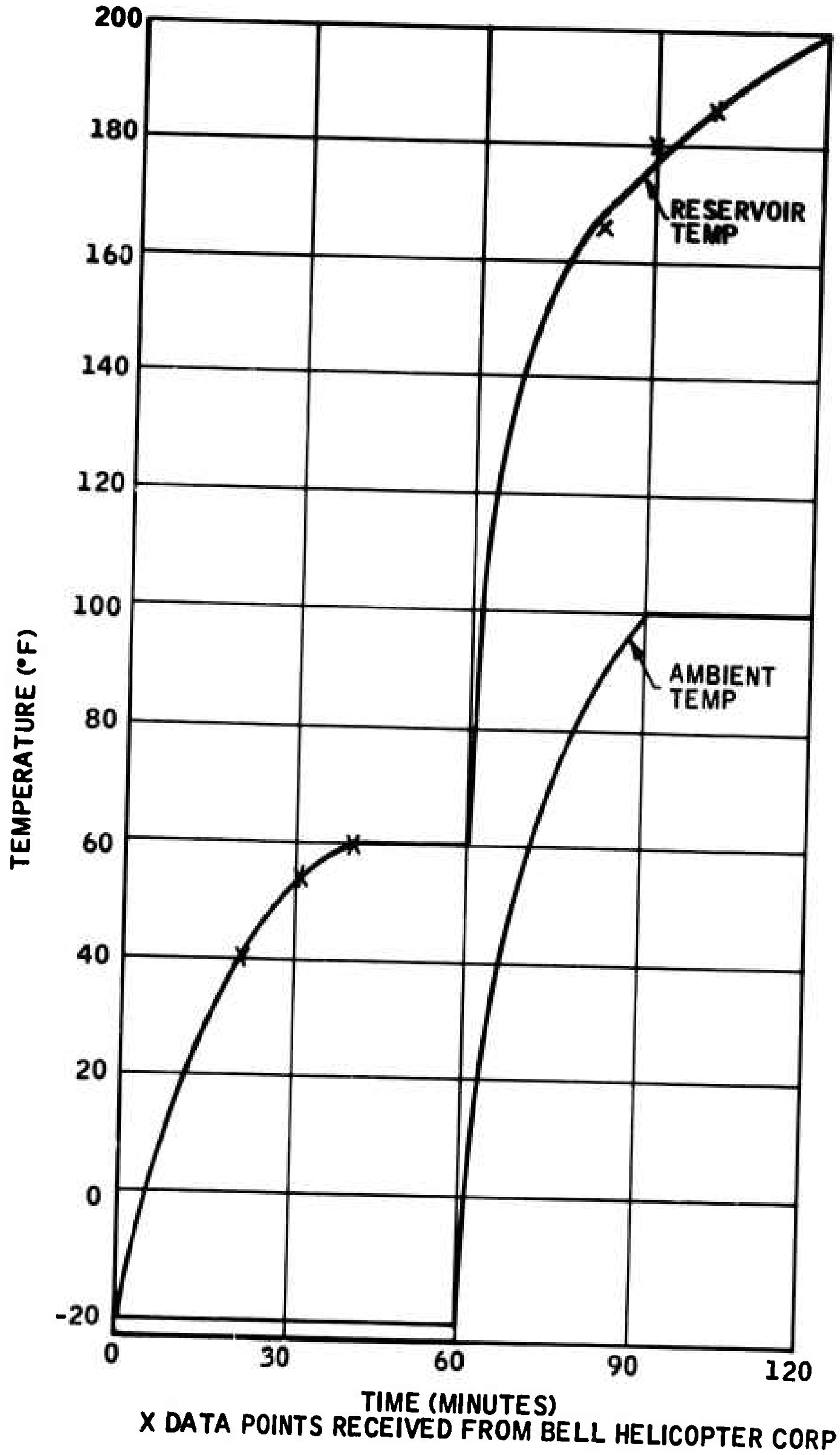


Figure 52. Simulation Test Temperature Cycle.

Data Analysis and Failure Criteria

The periodic performance check data were analyzed for frequency response (phase lag and amplitude ratio) and for SAS shorted hi-pass null, noise, linearity, and scale factor. Failure limits from Appendix II were then applied to determine if the system was functioning within its proper limits.

RESULTS

A summary of the performance check data obtained during the flight simulation tests is given in Table XI. In addition, the shorted hi-pass gain curves and bode plots of the frequency response are shown in Figures 53 to 66.

Three apparent failures occurred during the flight simulation tests. During the second performance test, the SAS null was slightly greater than its failure limit of 0.075 in.; the null was 0.080 in. The null shift is believed to have been caused by the trim valve. The trim valve is a needle valve and is not designed for environmental testing. It was decided to renull the SAS and to continue testing. It should be noted that no further null shift failures occurred.

After the fifteenth cycle, a frequency response test was attempted. The system had a poor output wave form, low straight-through gain (0.016 in./deg/sec), and 0.250 in. offset between the shorted hi-pass and hi-pass condition. Normal offset is about 0.050 in. The amplifier cascade was removed and cleaned. A piece of magnesium silicate was found blocking the power nozzle of the output amplifier. The piece was removed and the system was retested. The shorted hi-pass test was run, and system gain was 0.024 in./deg/sec. In an attempt to run the frequency response test, the system became extremely noisy (±0.075 in.) and exhibited low-shorted hi-passed gain (0.016 in./deg/sec). The system was completely taken apart and cleaned. A great deal of contamination was found in the rate sensor. The existing 10-micron line filter was removed and the element was replaced. In addition, a second 10-micron line filter was added in series with the existing filter for redundancy in case of a filter failure. This new filter had its bypass removed so that all fluid would be forced to pass through the element. When the clean filters were installed on the system, it was noticed that pump pressure required to flow 2.86 gpm through the system was now 60 psi, where previously it was 110 psi. This difference of 50 psi is exactly the bypass pressure of the old filter. It was concluded that the filter had always been bypassing and that contamination buildup finally caused a system failure. After the new filters were installed, the system passed the performance test.

TABLE XI. PERFORMANCE TEST DATA SUMMARY

Parameter	Failure Limits	Initial	1	2	3	4	5	6
Phase Angle (deg)	<50°	20	14.4	14.4	21.6	35.0	36.0	21.6
Amplitude Ratio (in./deg/sec)	0.0110 → 0.0234	0.0172	0.0135	0.0206	0.0150	0.0118	0.0140	0.0155
Linearity (%)[1]	0→23.7	8.7	4.2	4.8	5.9	10.5	6.9	12.7
Noise (in.)[1]	±0.020	±0.014	±0.016	±0.020	±0.075 ±0.020	±0.015	±0.055 ±0.016	±0.016
Null (in.)[1]	±0.075	0	+0.016	-0.080[3]	0[3]	-0.025	0.015[3]	0.020
Scale Factor (in./deg/sec)[1]	0.0188 → 0.0400	0.0294	0.0253	0.0281	0.016 0.0220	0.0281	0.0105 0.0238	0.0241
Range (in.)[1]	±0.300	±0.380	+0.364 +0.396	+0.460 -0.300	±0.380	+0.405 -0.355	+0.365 -0.395	+0.360 -0.400
Null versus P_s (in.)[1]			-0.048	-0.008	0.004	-	0.024	0.052

1. Shorted hi-pass
2. Where two numbers appear, the upper one is before the failure. Range is the only exception.
3. After each failure the output was renulled.

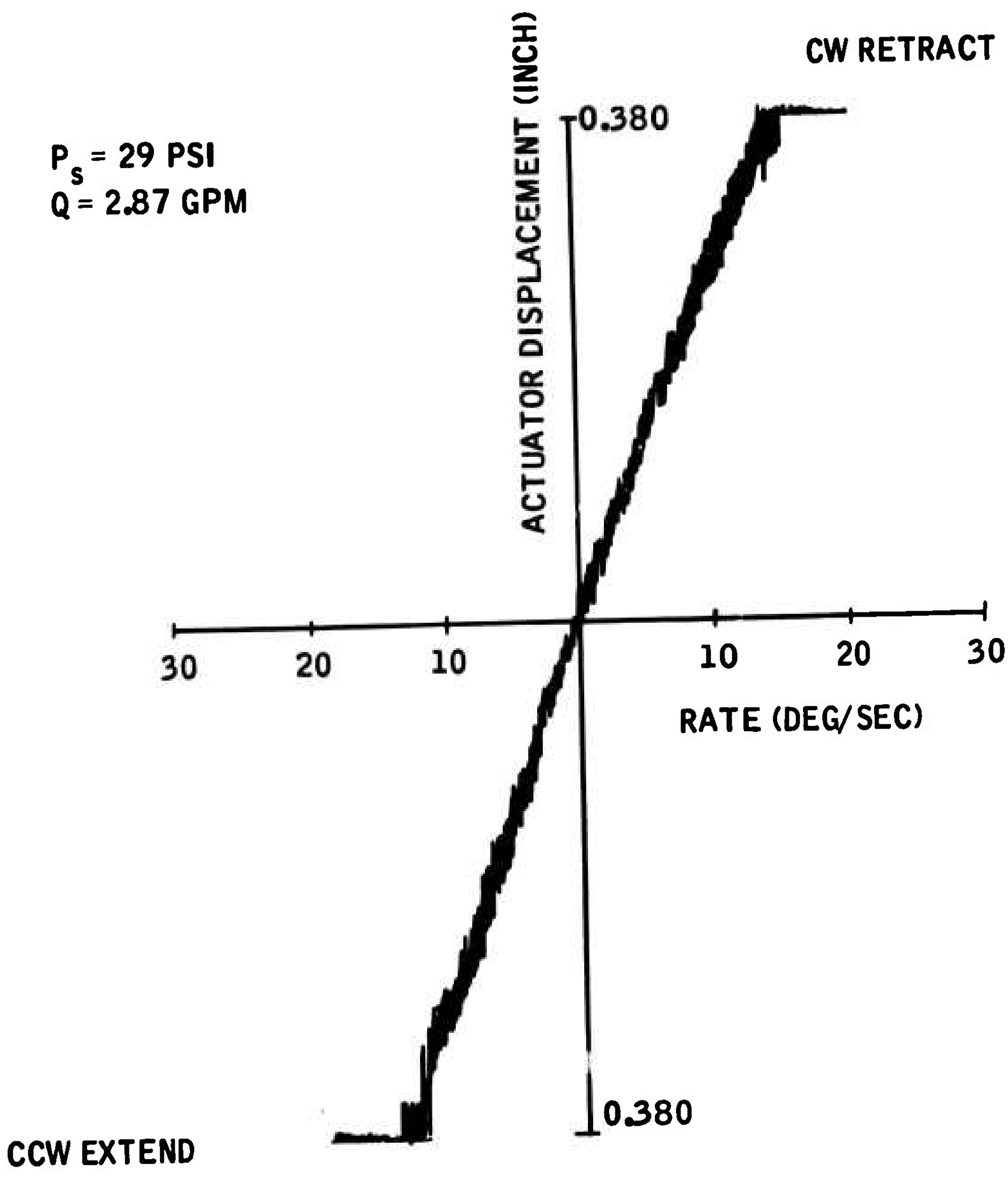


Figure 53. SAS Actuator Output Versus Rate Input, Shorted Hi-pass, Initial Performance.

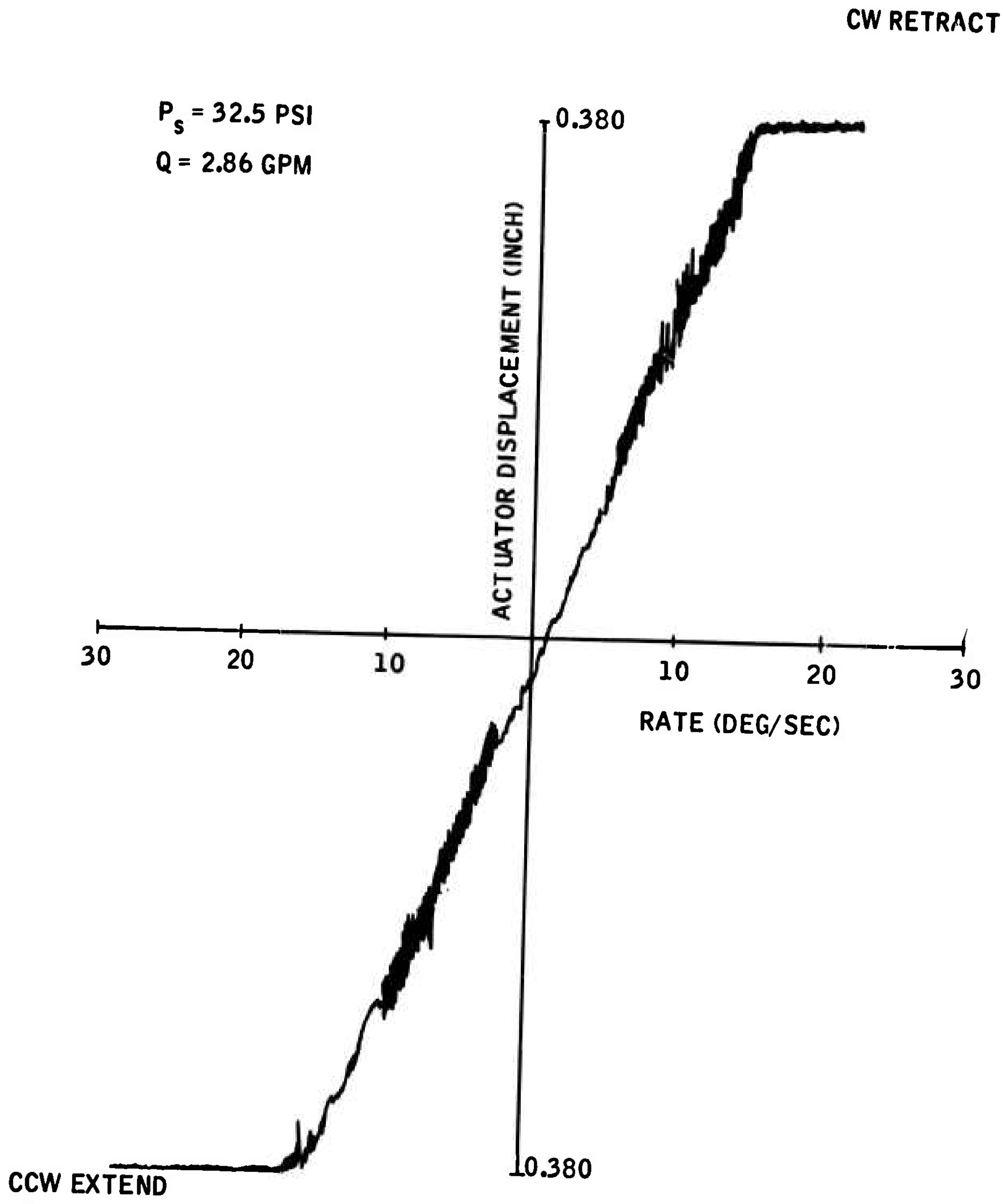


Figure 54. SAS Actuator Output Versus Rate Input After Fifth Cycle.

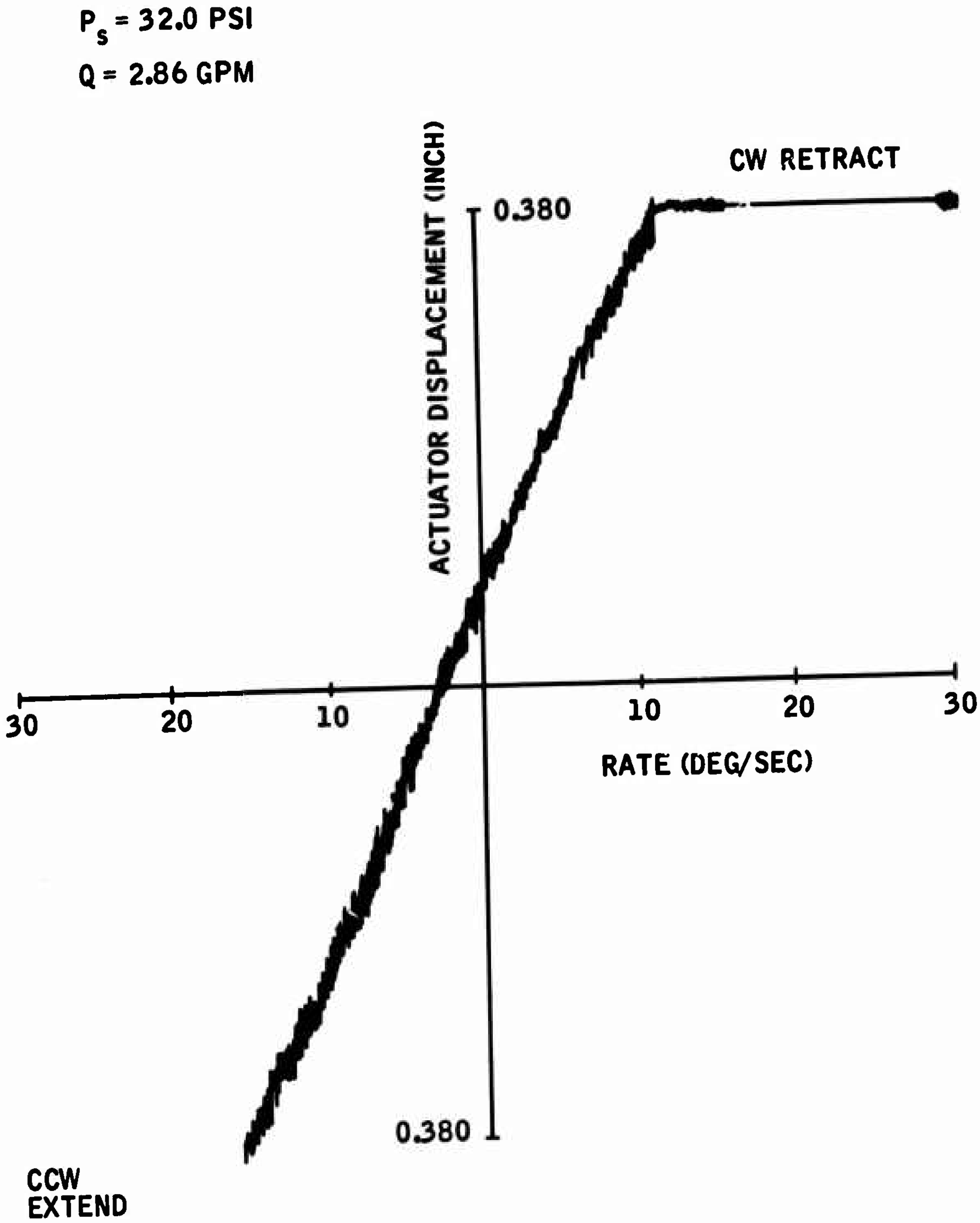


Figure 55. SAS Actuator Output Versus Rate Input After Tenth Cycle.

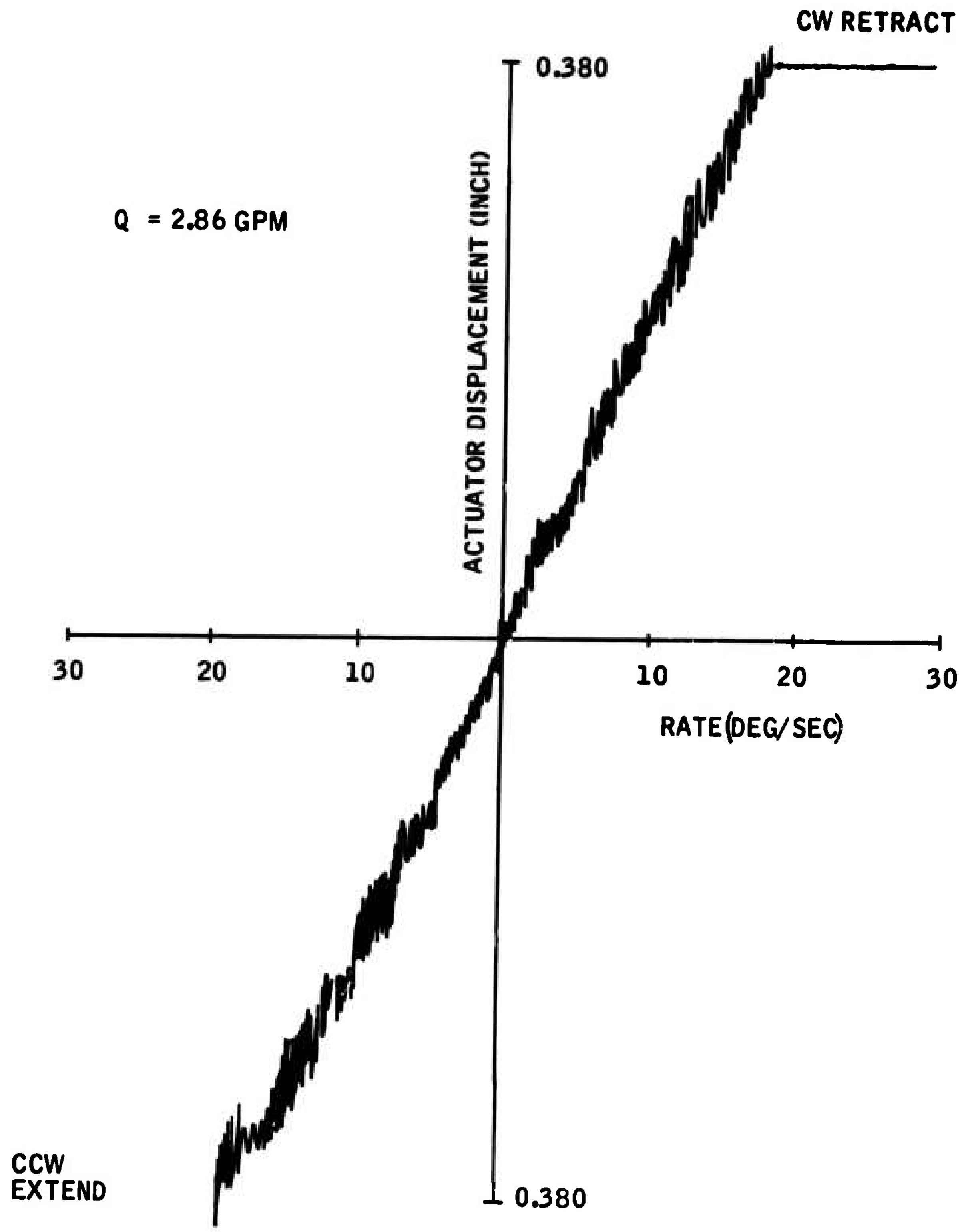


Figure 56. SAS Actuator Output Versus Rate Input After Fifteenth Cycle.

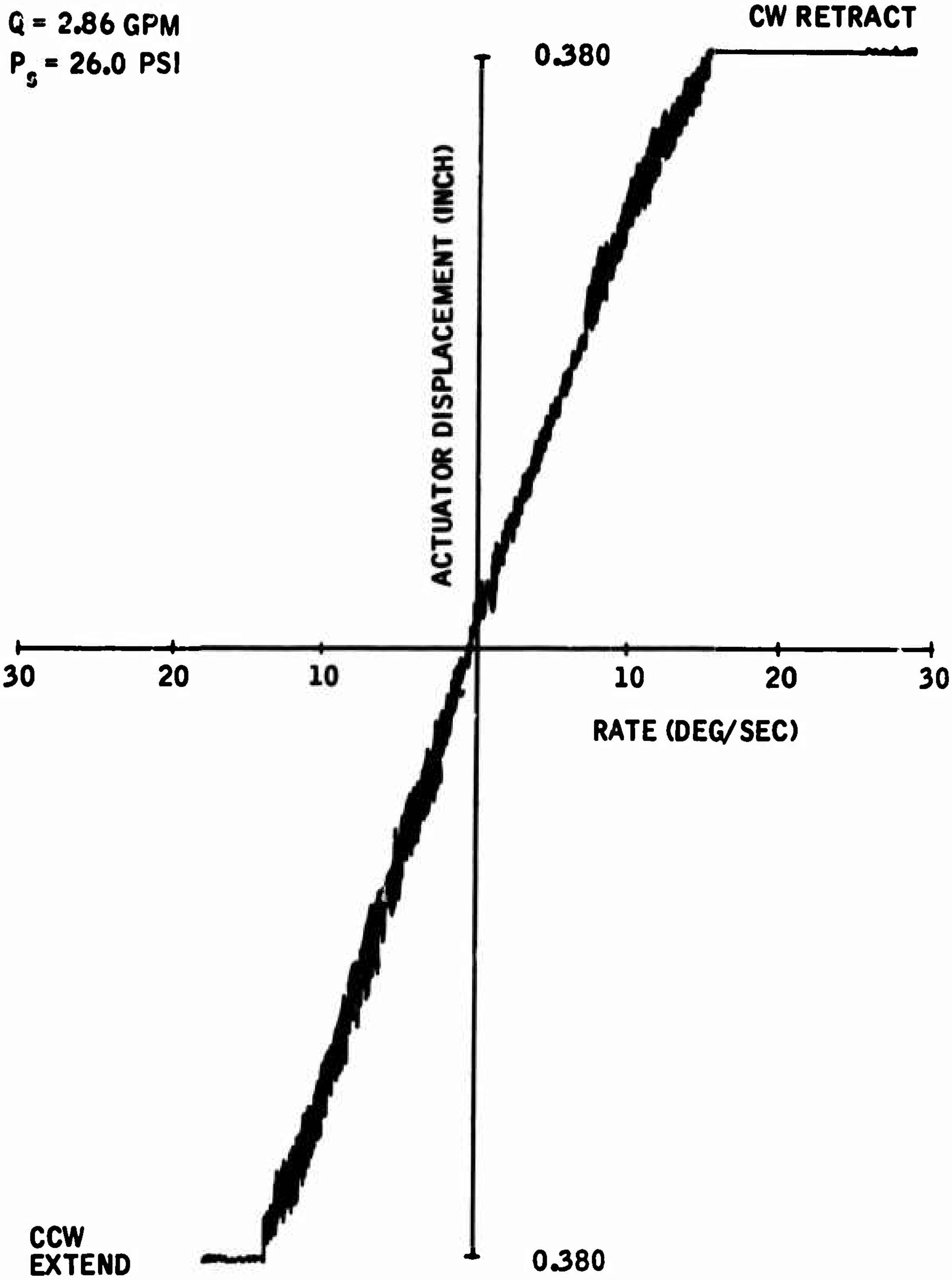


Figure 57. SAS Actuator Output Versus Rate Input After Twentieth Cycle.

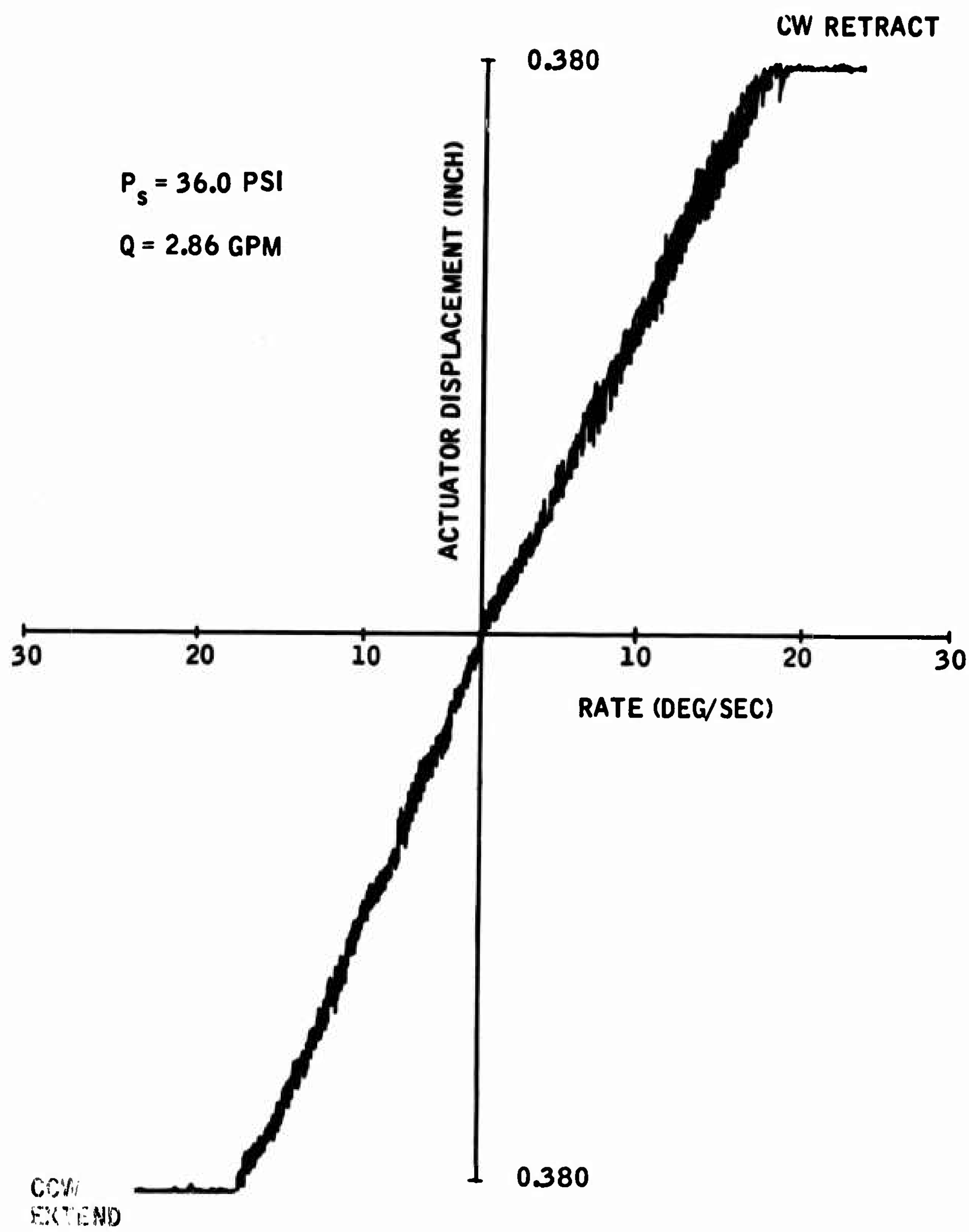


Figure 58. SAS Actuator Output Versus Rate Input After Twenty-Fifth Cycle.

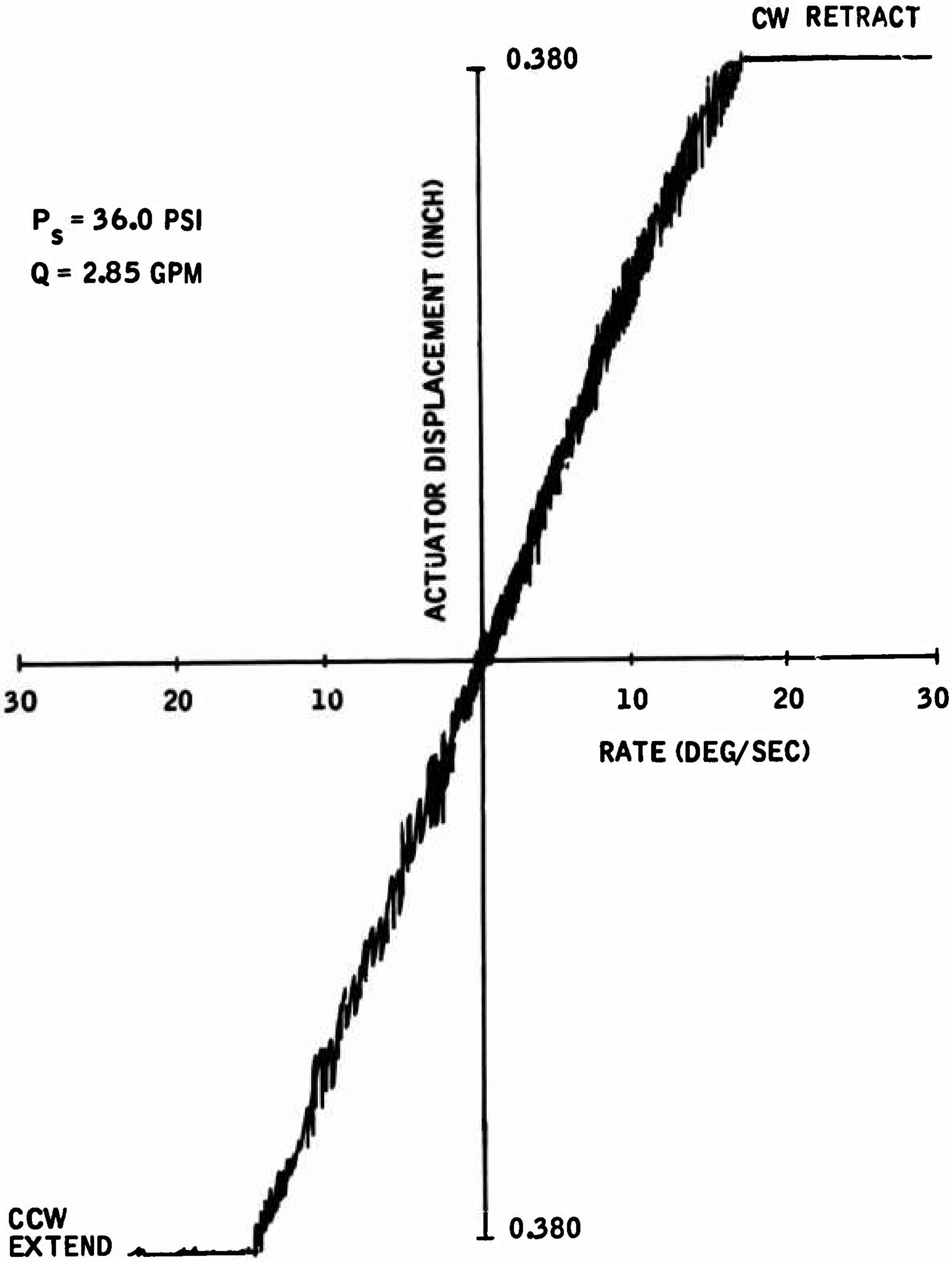


Figure 59. SAS Actuator Output Versus Rate Input, Final Performance.

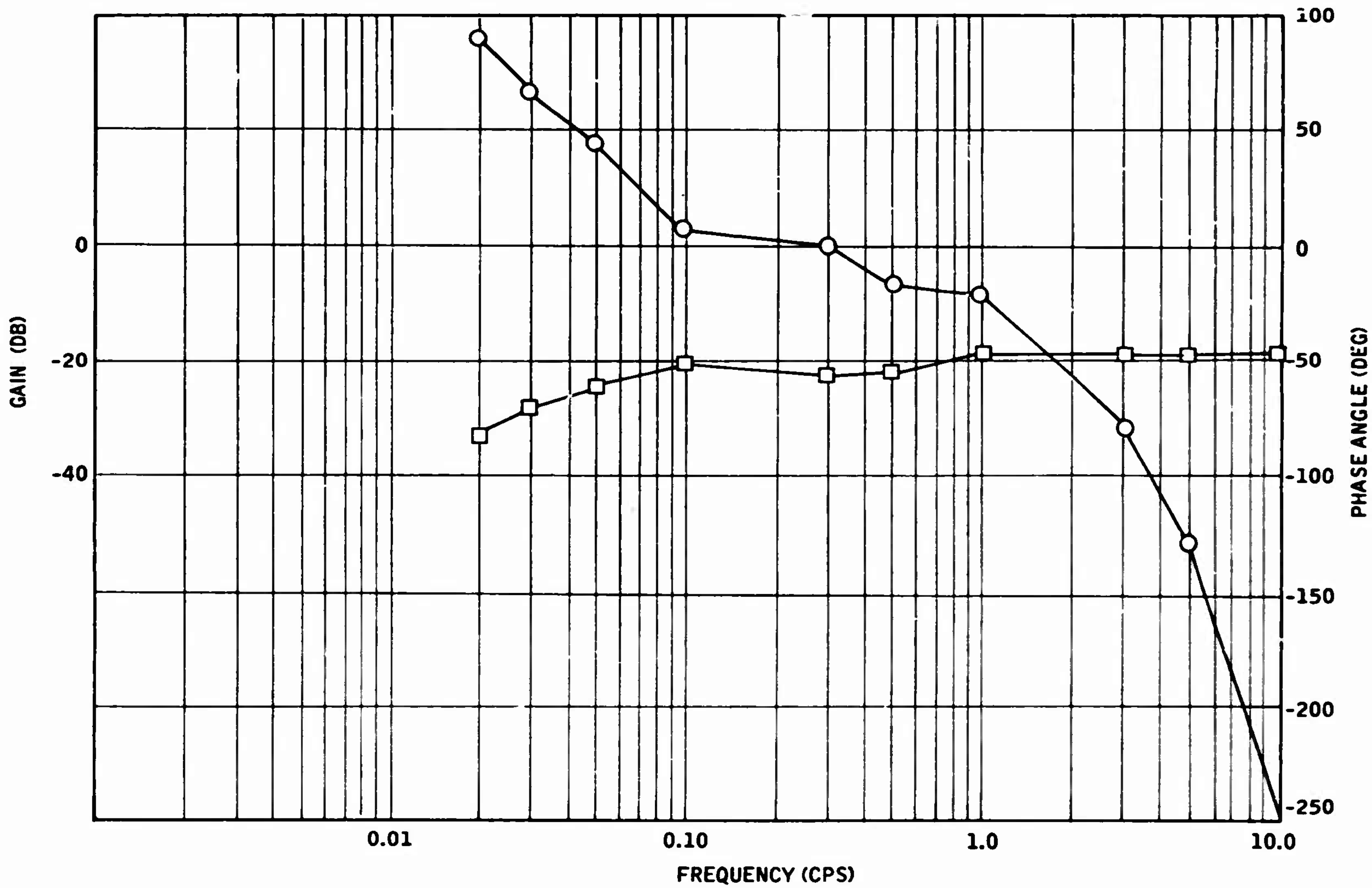


Figure 60. SAS Open-Loop Frequency Response, Initial Performance.

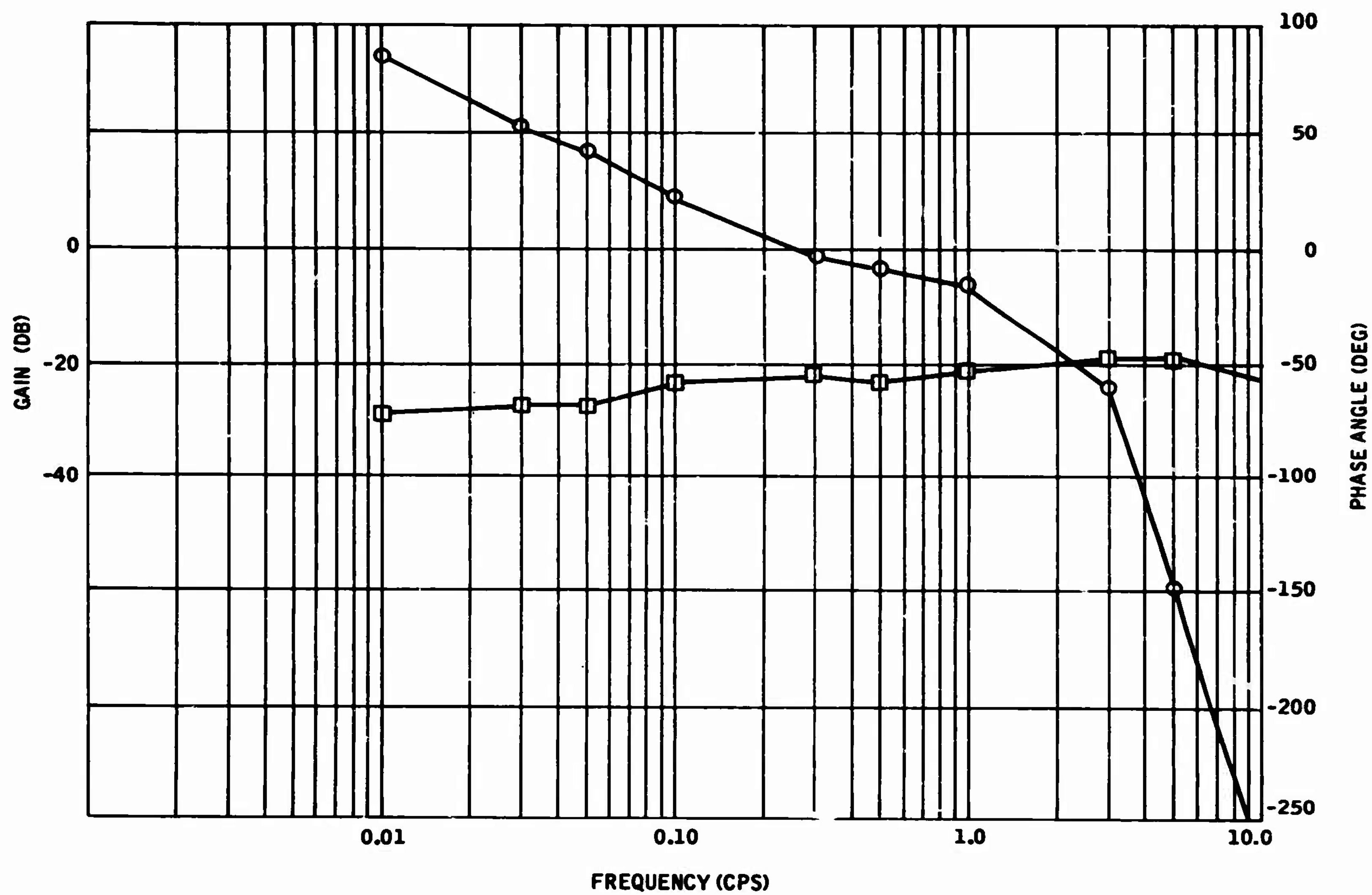


Figure 61. SAS Open-Loop Frequency Response After Fifth Cycle.

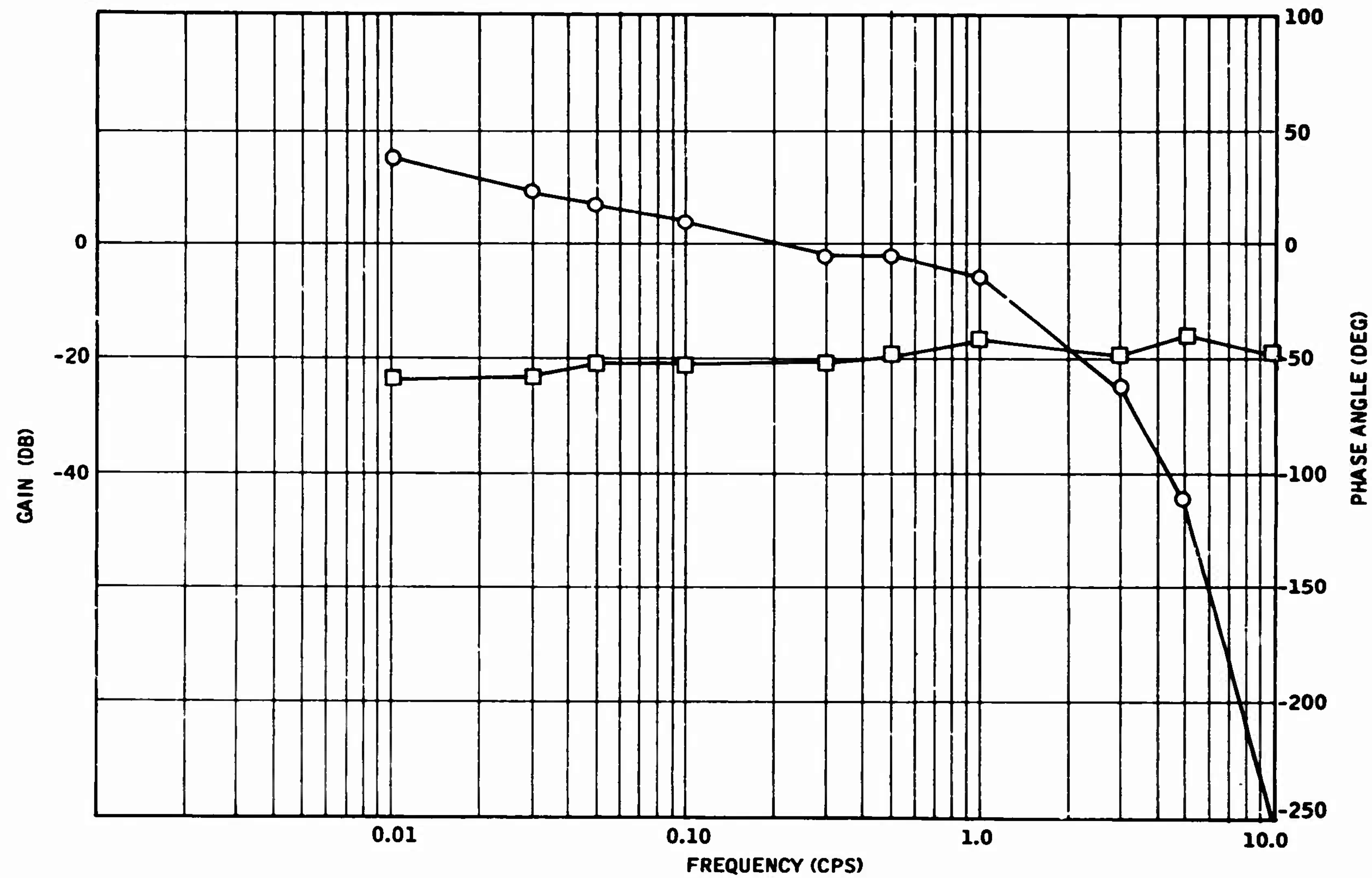


Figure 62. SAS Open-Loop Frequency Response After Tenth Cycle.

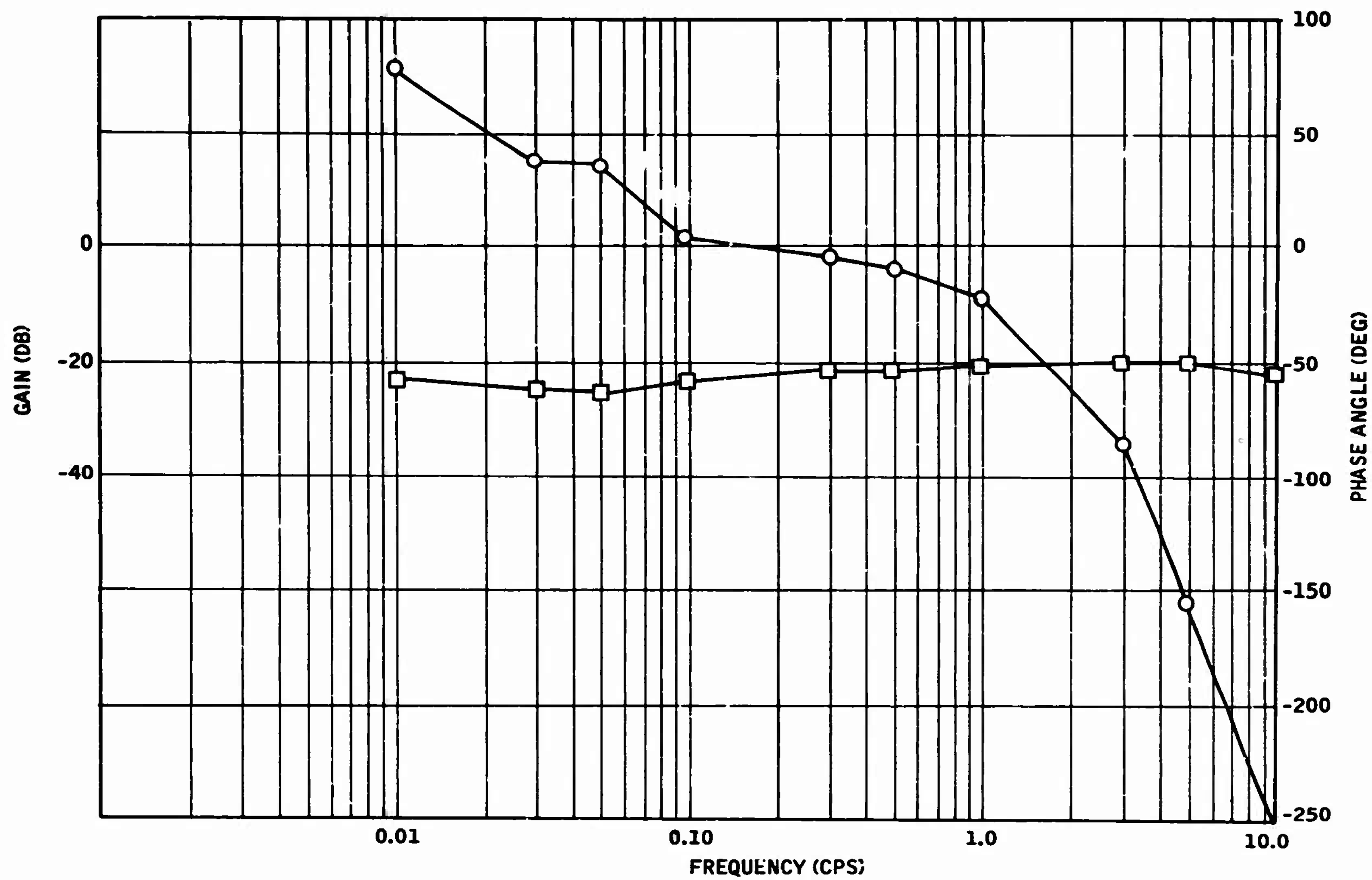


Figure 63. SAS Open-Loop Frequency Response After Fifteenth Cycle.

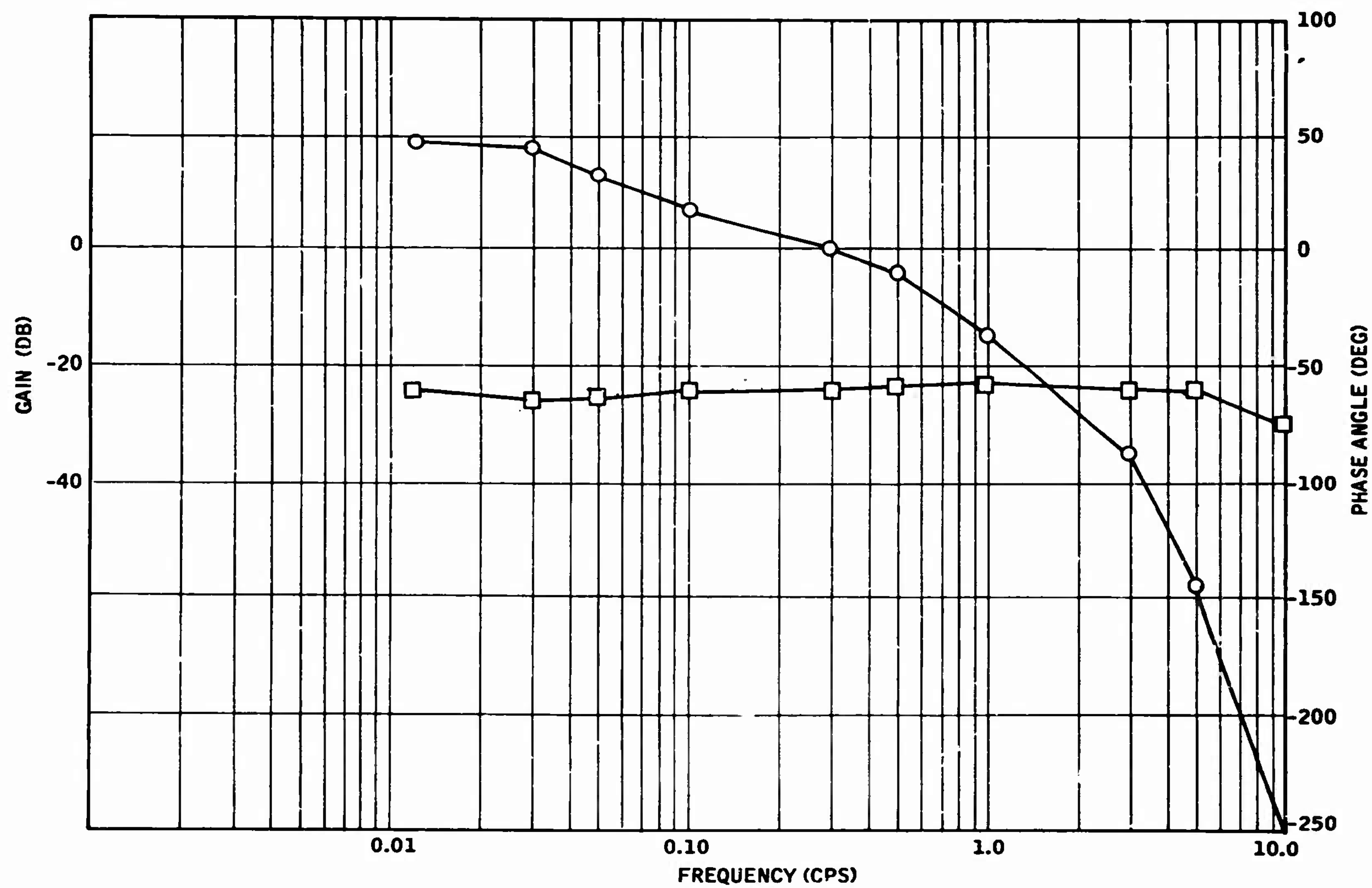


Figure 64. SAS Open-Loop Frequency Response After Twentieth Cycle.

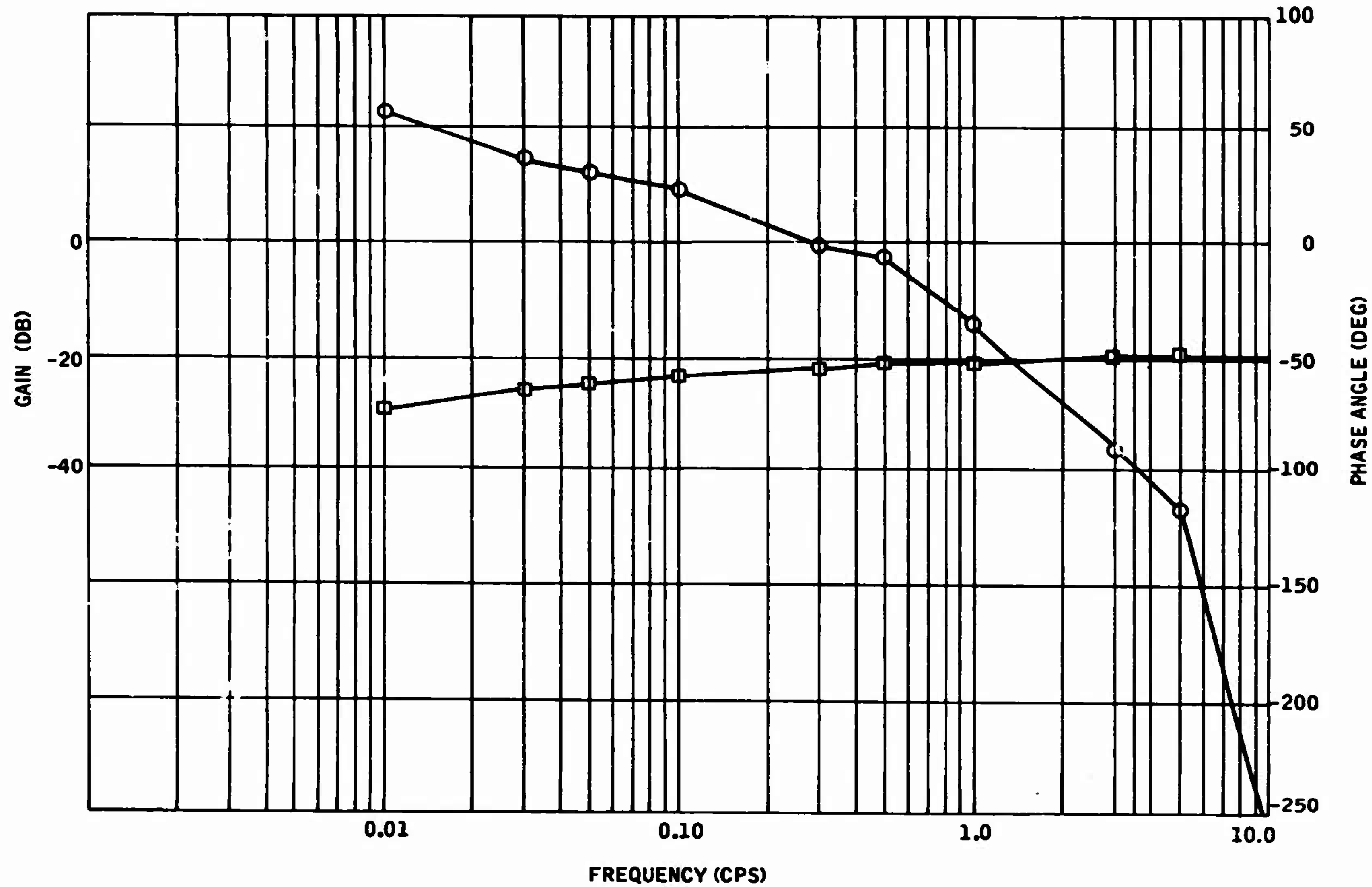


Figure 65. SAS Open-Loop Frequency Response After Twenty-Fifth Cycle.

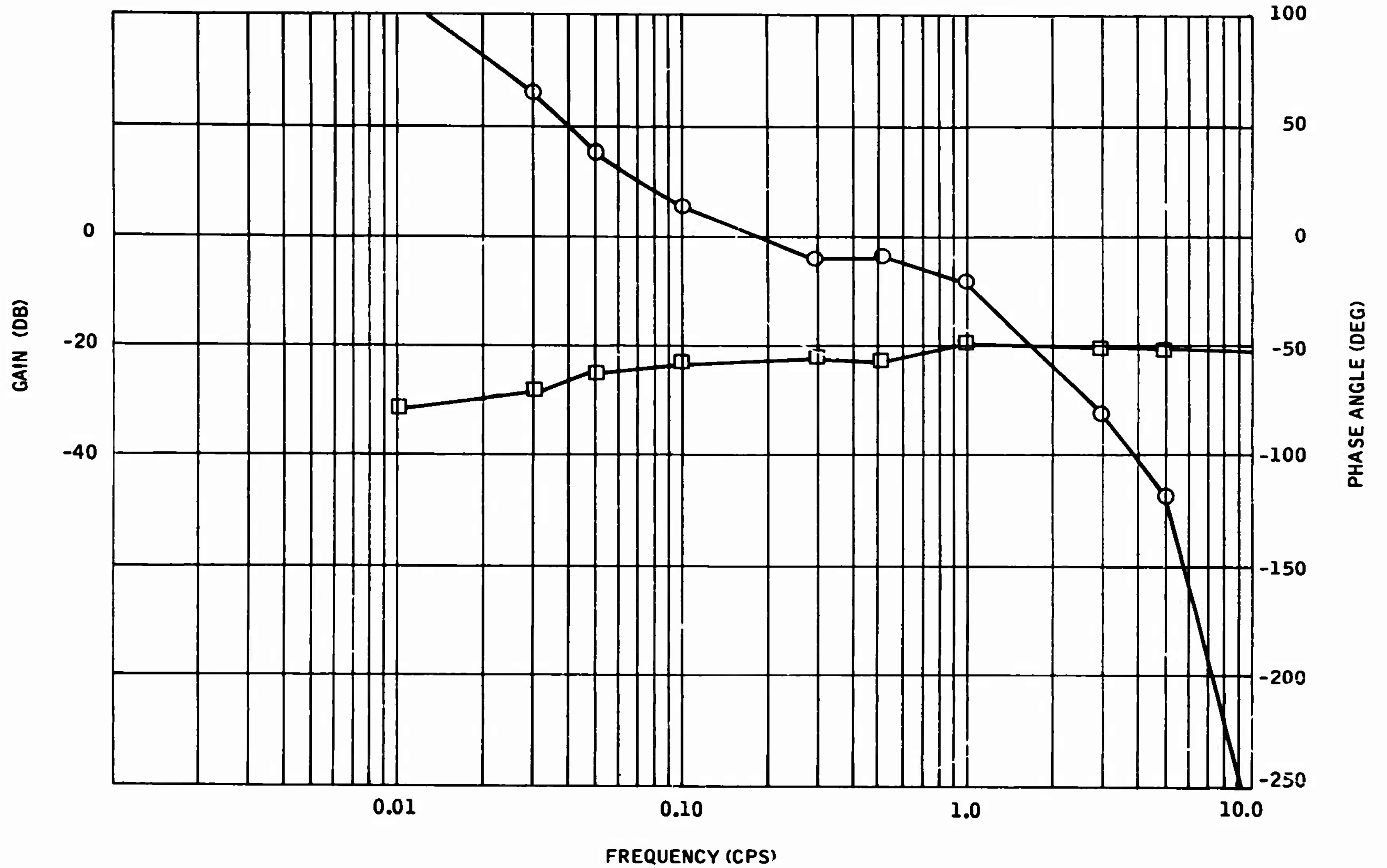


Figure 66. SAS Open-Loop Frequency Response, Final Performance.

A third failure occurred after the twenty-fifth cycle. Again, the shorted hi-pass test was concluded successfully and the frequency response test was attempted. The system was noisy (±0.055 in.) and had low-shorted hi-pass gain (0.0105 in./deg/sec). The rate sensor was removed and taken apart. It was very clean inside, but it was cleaned anyway and put back in the system. The system was retested but still exhibited low gain and high noise. The entire system was then thoroughly cleaned, restoring the system performance for the remainder of the flight simulation tests.

At the beginning and completion of the flight simulation tests, a closed-loop test was conducted. The purpose of the test was to show improved aircraft damping ratio from 0.3 to about 0.6. Table XII lists the percent overshoot and equivalent second-order damping for free and augmented aircraft during the three flight conditions. Data were determined from the β trace on the closed-loop response data and were obtained during wind gust inputs (β) and pilot rudder commands (θ). The data showed that the SAS increased the damping to 0.6.

TABLE XII. CLOSED-LOOP RESPONSE

Flight Condition	+β				-β				+θ				-θ			
	Initial		Final		Initial		Final		Initial		Final		Initial		Final	
	%O.S.	γ	%O.S.	γ	%O.S.	γ	%O.S.	γ	%O.S.	γ	%O.S.	γ	%O.S.	γ	%O.S.	γ
60 Knots-Free	0.27	0.39	0.30	0.36	0.30	0.36	0.30	0.36	0.29	0.37	0.26	0.40	0.30	0.36	0.20	0.46
Aug.	0.03	0.75	0.05	0.69	0.09	0.61	0.06	0.67	0.06	0.67	0.06	0.67	0	0.90	0.06	0.66
90 Knots-Free	0.30	0.36	0.30	0.36	0.33	0.33	0.33	0.33	0.28	0.38	0.33	0.33	0.33	0.33	0.30	0.36
Aug.	0.05	0.69	0.03	0.75	0.12	0.56	0.06	0.65	0.08	0.63	0.08	0.63	0.10	0.59	0.10	0.60
120 Knots-Free	0.30	0.36	0.30	0.36	0.33	0.33	0.33	0.33	0.35	0.32	0.27	0.39	0.26	0.40	0.30	0.36
Aug.	0.06	0.67	0.03	0.75	0.13	0.55	0.10	0.59	0.07	0.65	0.08	0.63	0.15	0.52	0.08	0.63

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13. ABSTRACT

The objective of this contract was to develop quantitative information concerning the reliability and maintainability of hydraulic fluidic components and systems. This was accomplished by testing a feasibility-model hydraulic single-axis stability augmentation system (SAS) under conditions simulating actual flights of a UH-1B helicopter and, along with 15 of each type of component making up the SAS, life testing under environmental conditions of 0.5-g and 2.0-g vibration, temperature from -30°F to +200°F, and cycling of the component input signals. Also tested were 15 bistable amplifiers. The components were divided into environmental and nonenvironmental groups, with the environmental group divided into groups subject to 50-micron oil and 10-micron oil. This made up the 15 components, five in each of the three groups.

The feasibility SAS and the components making up the SAS completed the testing with no failures. While the bistable amplifiers did not meet the failure limits, they still had enough gain to switch another like amplifier. The results of this program show that fluidic components and systems are very reliable.

Since fluidic components appear to fail only in a wearout mode, more components should be tested for longer periods of time to determine their life and how they fail.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hydrofluidic						
Reliability						
Vortex Rate Sensor						
Proportion and bistable amplifiers						
Electrical to fluid transducers						
Bellows						
Hydrofluidic Stability Augmentation System						
Flight Simulation of FSAS						